2010 5th International Symposium on Wireless Pervasive Computing (ISWPC)

An Exclusive Self-Coexistence (ESC) Resource Sharing Algorithm for Cognitive 802.22 Networks

P. Camarda, C. Cormio and C. Passiatore
DEE–Politecnico di Bari
v. Orabona, 4 – 70125, Bari, Italy
Email:{camarda, c.cormio, c.passiatore}@poliba.it;

Abstract—**IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) which exploits the cognitive radio technology in order to use spectrum holes in the TV frequency band. The standard allows the sharing of unused spectrum allocated to the Television Broadcast Service without causing harmful interference to licensed users like TV transmitters and receivers. It is essential to perform an efficient channel assignment in cognitive 802.22 networks. In this paper we propose an original resource sharing algorithm which, working in a multichannel environment, aims at assigning channels to WRANs in such a way to satisfy their request and avoid completely the interference among them. It also 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 multichannel resource sharing scheme is proved through simulations, and in particular the number of assigned slots is evaluated. The results show that the algorithm makes a resource assignment which satisfies the requests avoiding interference among overlapping WRANs.**

I. INTRODUCTION

IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) using in an opportunistic way the white spaces in the TV frequency spectrum. The IEEE 802.22 WRAN standard exploits cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the Television Broadcast Service on a non-interfering basis. The most important issue is that the cognitive radio users must not interfere with primary users, like TV transmitters and receivers.

In the following we give a quick overview of the cognitive 802.22 standard. The 802.22 working group (WG) was formed in November 2004 [1]. The IEEE 802.22 WG is being developing a CR-based Wireless Regional Area Network (WRAN), Physical (PHY) and Medium Access Control (MAC) layers by unlicensed devices in the spectrum that is currently allocated to the Television (TV) service.

In the 802.22 system each WRAN consists of a base station (BS) serving fixed wireless subscriber called customer premise equipments (CPE). The BS manages the medium access in its own WRAN.

The topic we deal with in this paper is the resource sharing, which represents an issue in cognitive 802.22 networks.

Two types of inter-BS dynamic resource sharing mechanism are provided by the 802.22 standard, namely On-Demand Spectrum Contention [2] and Resource Renting. The former mechanism is a spectrum sharing scheme which is based on a contention: for this reason ODSC has some limit to guarantee the QoS satisfaction. The latter mechanism is a spectrum sharing scheme that allows BSs to share one or more channels by selectively renting candidate (surplus) channels of neighboring cells. In the context of spectrum sharing scheme, Chen et al. [3] expose an auction-based inter-BS spectrum sharing for cognitive 802.22 networks which exploits a credit token. In [4] a resource allocation solution, called Dynamic Frequency Hopping (DFH), is presented. It allows to perform data transmission and spectrum sensing in parallel without interruptions. Furthermore, it uses only $N+1$ channels instead of $2N$ for N WRANs. Brahma et al. [5] propose a graph theoretic technique and utility graph coloring for allocating spectrum to different BSs. The above schemes are only feasible when there is resource oversupply, which is not always true when the available resources are not sufficient to assign one channel to each WRAN.

In this paper we propose a novel multi-channel resource sharing algorithm for cognitive 802.22 networks, focusing on the case the number of available channels is smaller then the number of WRANs. The proposed scheme performs an efficient channel assignment taking into account the overlaps among WRANs in order to avoid interference situations. The assignment is made in opportunistic way, based on the channels which are detected free with a periodical action of sensing. The main advantage of the scheme is that the assignment is made based on the QoS requirements of each WRAN, in such a way that the number of slots assigned to each WRAN satisfies its needs. A further aspect is represented by the spatial diversity; in fact our scheme is able to make an efficient assignment also when not all the WRANs are covered by all the available channels.

The paper is structured as follows. In Section II the system scenario is analyzed. In Section III the multichannel resource sharing scheme is exposed, completed by a simple analythical model. Section IV shows simulation results and Section V draws the conclusions.

II. SYSTEM SCENARIO

We introduce a model for resource sharing in a scenario where the number of available channels is not sufficient to assign one channel to each WRAN. Our resource sharing method is introduced with the help of an example.

The scenario is referred to a cognitive 802.22 wireless network.With reference to [4], we assume that neighboring

978-1-4244-6857-7/10/$26.00 ©2010 IEEE

WRANs form cooperating communities in order to coordinate channel access. Successively the WRANs constituting the community elect a coordinator among their BSs. The mechanism used to elect the coordinator is based on priority, as explained in [4]. The communication between each BS and the coordinator is based on the Coexistence Beacon Protocol (CBP) mentioned in [6]. CBP beacons carry information about cells and the down/upstream bandwidth allocation for the users. The 802.22 Standard specifies time slotted operations. It introduces the concept of superframe, which consists of 16 MAC frames of 10ms each [7]. The MAC frame is made of two parts, namely downstream subframe(DS) and upstream (US) subframe. The DS subframe contains packets coming from the BS in downstream toward a CPE, while the US subframe has packets transmitted in upstream from the CPEs to BS. The frame is composed by multiple time slots.

The developed algorithms have been applied to a specific scenarios but their validity is general. Specifically the scenario we refer to is shown in fig.1, where 5 WRANs are in overlapping situation. Moreover we assume that $ChannelA$ is available for all WRANs, while $ChannelB$ is available only for $WRAN2-3-4$, which implements the concept of spatial diversity. Obviously the WRANs cannot transmit all simultaneously. We introduce a method for the assignment of time slots, in such a way to avoid harmful interference among WRANs. This means that the time slot over one channel, can be assigned simultaneously to WRANs which are not overlapping among them.

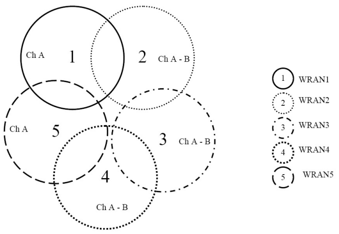

Fig. 1. Example of overlapping WRANs

Each BS is supposed to communicate with the coordinator which, once obtained all the informations it needs, is able to implement solutions for resource sharing optimization. In particular we assume that each BS is able to know the WRANs overlapping with itself and to convey the information to the coordinator. The coordinator, upon collecting the topology informations, creates a table called overlap table. In particular, element (j,i) is equal to 1 when WRANj overlaps with WRANi.

In order to take into account the *spatial diversity*, i.e. the availability of some channels only for some WRANs, another table is needed. According to the channel availability, the coordinator generates the $Channel\ Table$. With reference to $Channel\ Table$, element (i,j) equal to 1 means that $WRANi$ is in a zone covered by Channel$j$; on the contrary, element(i,j) is equal to 0 when $WRANi$ is not covered by Channel$j$. The $Channel\ Table$ is periodically updated by the coordinator after each sensing action.

TABLE I
OVERLAP TABLE FOR FIG.1

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

TABLE II
CHANNEL TABLE

	Channel A	Channel B
W1	1	0
W2	1	1
W3	1	1
W4	1	1
W5	1	0

We built a Matlab tool which, starting from Tab. I, computes the combinations of WRANs allowed to transmit simultaneously. Tab. III shows the allowed combination, in the contest of the considered scenario. As an example, $Possibility1$ means that $WRAN1$ and 3 can transmit simultaneously, being made of non overlapping WRANs. The same informations are reported on the last column of Tab.III, which shows the state_vectors. Tab. III shows all the allowed combinations of WRANs, which is valid for the single channel case. The table for the multiple channel case will be shown in the following. In this example we assume two available channels, but the exposed method is valid for any number of channels. In particular, the WRANs which have the $opportunity$ to transmit during the slot, using the two channels, are given by the union of two $possibilities$ of tab.III. Our method evaluates all the simple dispositions without repetitions, of the $possibilities$ in the available channels. The procedure of melting of two possibilities gives as a result vectors called $opportunities$.

TABLE III
ALLOWED WRAN COMBINATIONS

Possibility	WRAN	state_vector
possibility 1	1,3	1,0,1,0,0;
possibility 2	1,4	1,0,0,1,0;
possibility 3	2,4	0,1,0,1,0;
possibility 4	2,5	0,1,0,0,1;
possibility 5	3,5	0,0,1,0,1;

In the final $opportunity$ it is necessary to avoid that a channel is assigned to a WRAN not covereed by the channel itself, according to $Channel\ Table$. To explain the method we use an example. Let us assume that $possibility1$ is implemented on $ChannelA$, $possibility2$ is implemented on $ChannelB$. According to this assignment, what happens is that: $WRAN1$ and $WRAN3$ could transmit using $ChannelA$; and $WRAN1$ and $WRAN4$ could utilize $ChannelB$. In the proposed example we assume that $WRAN1$ cannot use $channelB$: i.e. the resulting combination is: $WRAN1$ and $WRAN3$ use

$ChannelA$; and $WRAN4$ utilizes $ChannelB$. Furthermore we assume that a BS is able to manage only one time slot at a time, because otherwise the BS should have several network interfaces. The coordinator, according to tables III and $Channel\ Table$, calculates all the possible allowed WRAN combinations, for two channels. For the scenario in fig. 1 the final allowed WRAN combinations are shown in Tab.IV.

TABLE IV
FINAL ALLOWED WRAN COMBINATIONS

opportunity	Ch. A	Ch. B	state_vector
opportunity 1	1,3	2, 4	1,1,1,1,0;
opportunity 2	3,5	2, 4	0,1,1,1,1;

In Tab.IV there are only 2 $opportunities$. The reason is that, in the process of melting the possibilities, the algorithm erases the combinations which are repeated or included in other solutions. As shown previously, the union of $possibilities$ 1 and 2 of Tab.III gives the final combination $WRAN1-3$ on channel A, and $WRAN4$ on channel B. The above solution is not in Tab.IV, because it is contained in the $opportunity1$ of Tab.IV. $Opportunity1$ has been obtained by the union of $possibilities1$ with $possibility3$.

What happens is that the coordinator at the beginning of the superframe decides, which is the best combinations of WRANs to assign each slot. The coordinator makes the choices by using the algorithm that we propose in the following section.

III. RESOURCE ALLOCATION ALGORITHM

In this Section the resource sharing algorithm is explained in detail, referring to the case where a single channel is available. The extension to the multichannel case can be easily obtained considering the appropriated table of allowed WRAN combinations. The goal of the algorithm is the fairness of the assignment. Each BS estimates, for each superframe, how many slots its WRAN needs and, at the beginning of a superframe, the BS communicates to the coordinator this information. After that the reception of all the slot 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, and $request_i$ the number of slots requested by WRANi. It deduces that the sum of all p_i 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 one channel. For each time slot, the coordinator must choose one of the above combinations of WRANs to assign the slot. In the last column of Tab.III the state_vector corresponding to each allowed combination is shown. The state_vector is a vector where element i represents the total number of slots assigned to WRAN i. As an example, vector (1,2,2,4,1) represents the state where WRAN1 has been totally assigned 1 time slot, WRAN2 2 time slots and so on. The state_vector is updated slot by slot.

At the beginning of each superframe, the coordinator receives from the BSs the slot requests and computes the p_i. At the beginning of the following superframe, if the slot requests have changed, the coordinator resets the state_vector and computes a new one, based on the new values of p_i. On the opposite, if the values of p_i stay the same, the coordinator uses the previous state_vector as a starting point.

In the following we expose the chosen criteria exploited to determine the best final state_vector. Specifically, the best state_vector 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 slots assigned to $WRANi$.

For the first slot of the first superframe the best choice is obtained comparing all the values given by eq.2 to the state_vectors corresponding to each combination. In the example of fig.1 5 $possibilities$ are feasible. Therefore, at the beginning, 5 different state_vectors are obtained by considering the 5 allowed transmission $possibilities$. In the subsequent slot, from each of these states 5 branches start, and so on for the other time slots. Each branch represents a possible choice for the current slot. It is possible to notice that after many time slots the number of states reaches a huge number.

Fig.2 shows the partial graph with the possible combinations obtainable after 3 time slots with 3 $possibilities$. The choices equivalent to a choice that has been already made are represented by a dashed line in fig.2. Tab. V shows the number of possible state_vectors obtained, at each step, with an increasing number of time slots, and having up to 15 available possibilities.

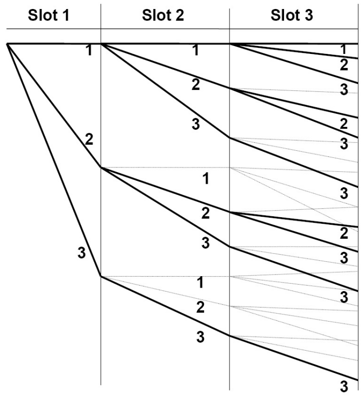

Fig. 2. Graph of possible choices

The elements of Tab.V can be calculated using the following formula:

$$n(e,s) = \sum_{i_1=1}^{e} \sum_{i_2=i_1}^{e} \cdots \sum_{i_s=i_{s-1}}^{e} 1, \tag{3}$$

TABLE V
NUMBER OF POSSIBLE $state\_vectors$

possibility number	slot1	slot2	slot3	slot4	slot5	...	slot15	...	slot30
1	1	1	1	1	1	...	1	...	1
2	2	3	4	5	6	...	16	...	31
3	3	6	10	15	21	...	136	...	496
4	4	10	20	35	56	...	816	...	5456
5	5	15	35	70	126	...	3876	...	$46\cdot10^3$
...						...		...	
15	15	120	680	3060	$11\cdot10^6$	...	$77\cdot10^6$	...	$11\cdot10^{10}$

where e is number of $possibilities$ and s is the number of time slots, i.e. they are respectively the indexes of the row and of the column. The index of the generic sum in eq. 3 starts from the index of the previous sum for the following reason. We want to exclude the state_vectors which are obtained as permutation of an already considered vector, as explained with reference to fig.2. Making each index start from the index of the previous sum is the necessary condition to avoid repetitions.

It is easy to see that n(e,s) can be evaluated recursively exploiting the following formula:

$$n(e,s) = n(e,s-1) + n(e-1,s). \tag{4}$$

where:

$$n(e,s-1) = \sum_{i_1=1}^{e} \sum_{i_2=i_1}^{e} ... \sum_{i_{s-1}=i_{s-2}}^{e} 1, \tag{5}$$

and:

$$n(e-1,s) = \sum_{i_1=1}^{e-1} \sum_{i_2=i_1}^{e-1} ... \sum_{i_s=i_{s-1}}^{e-1} 1. \tag{6}$$

In fact, $n(e,s)$ is made by s summations, where the first one has the index ranges from 1 to e; also $n(e-1,s)$ is made by s summations, but the first has the index varying from 1 to $e-1$. Then, considering $n(e-1,s)$ to obtain n(e,s) we have to add the elements obtained fixing $i_s = e$ and considering all the previous $s-1$ sums with index varying from the index of the previous sum up to e: the sum of these elements is exactly equal to $n(e,s-1)$.

In the following we prove that the criteria of our algorithm tries to satisfy the WRANs' slot requests. Our criterion aims at maximizing y in eq.2; it is possible to demonstrate that the optimal solution is obtained when $n_i = n \cdot p_i$, where n is the total number of assigned slots. This means that, 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:

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

Eq.7 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. Let us now prove the following inequality:

$$\sum_{i=1}^{N} p_i \ln(n_i) \leq \sum_{i=1}^{N} p_i \ln(np_i), \tag{8}$$

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

By drawing everything to the first member we obtain:

$$\sum_{i=1}^{N} p_i \ln(n_i) - \sum_{i=1}^{N} p_i \ln(np_i) \leq 0. \tag{9}$$

Given that the first member can be written as:

$$\sum_{i=1}^{N} p_i \ln \frac{n_i}{np_i}. \tag{10}$$

and that $\ln y \leq y-1$, see [8], we obtain:

$$\sum_{i=1}^{N} p_i \ln \frac{n_i}{np_i} \leq \sum_{i=1}^{N} p_i [\frac{n_i}{np_i} - 1]. \tag{11}$$

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

$$\sum_{i=1}^{N} p_i [\frac{n_i}{np_i} - 1] = \sum_{i=1}^{N} p_i \frac{n_i}{np_i} - \sum_{i=1}^{N} p_i = 0; \tag{12}$$

We proved that:

$$\sum_{i=1}^{N} p_i \ln(n_i) \leq \sum_{i=1}^{N} p_i \ln(np_i), \tag{13}$$

which means that first and second member become equal when $n_i = np_i$, i.e. $\sum_{i=1}^{N} p_i \ln(n_i)$ is maximized when $n_i = np_i$.

To find the best solution the coordinator should evaluate all possible state_vectors. For each of these it should calculate the result of eq.2, and finally choose the state which returns as result the highest value. It is worth noticing that the computational complexity is very high, because an huge number of calculations may be required, as shown in Tab.V. We propose a step by step algorithm. With this approach the coordinator takes, slot by slot, the best decision for the resource assignment to the WRANs, with a reduced computational complexity.

The step by step algorithm works as follows: At the beginning the coordinator computes all the possible $state\_vectors$ for the first time slot of the superframe; and, for each vector, it calculates the result of eq.2. The coordinator chooses the $possibility$ corresponding to the state_vector which returns the highest value. Hereafter we refer to this vector as $state\_vector1$. In the example in fig.1, the 5, possible $state\_vectors$ are shown in the last column of Tab.III. $State\_vector1$ is the starting point for selecting the best combination of WRANs in the subsequent slot. All the possible state_vectors are calculated, adding to $state\_vector1$ the state_vector for each element in Tab.III. The result of eq.2 is computed for all the state_vectors, and the WRAN combination which gives back the highest value as a result is chosen. The chosen WRAN combination becomes the starting point for the assignment process in the subsequent slot. The assignment process is repeated in each slot. In fig.3 a scheme which represents how the step by step algorithm works is shown. The example of fig.3 is referred to the scenario in fig.1, when only $ChannelA$ is available. Then the allowed WRAN combinations are represented in tab.III. The transmission probabilities used in the example of fig.3 are p_1=0.3, p_2=p_3=0.2, and p_4=p_5=0.15. Each column of fig.3 shows the possible state_vectors for a slot. These vectors are used to compute the result of eq.2, and finally, the vector which gives the highest result is chosen. The state_vector in the red square is the choice made by the coordinator.

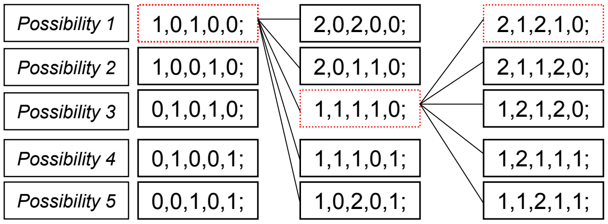

Fig. 3. Example of the step by step algorithm

Fig.3 highlights that the step by step algorithm has the same computational complexity for each slot, while the computational complexity of the general algorithm, as shown in tab.V, grows exponentially. Obviously the results obtained by the step by step algorithm are usually sub-optimal respect to the general case. To prove this, we built a Matlab tool by which we run simulations under scenarios obtained by varying the WRAN number, p_i vector, and overlapping table. We compared the state_vector obtained with the step by step algorithm with the state_vector obtained using the general algorithm. Due to the high computational complexity of the second algorithm, we could only compare simulations of few time slot duration. We find that the criterium exposed in this section, when applied step by step gives sub-optimal result.

IV. PERFORMANCE EVALUATION

We built a Matlab simulation tool for evaluating the performance of the proposed algorithm are evaluated. As explained in the previous section, due to the high computational complexity of the general algorithm, we run the Matlab code using the step by step algorithm.

In this Section we show the simulation results in two different cases: the first where the available resources are sufficient to satisfy the WRAN requests, the second where the WRAN requests exceed the available resources. We assume that the cases in which the WRAN requests exceed the available resources are represented in the figures by continuous curves. On the opposite, in the cases where the available resources outdo WRAN requests dotted lines are used. In all simulations we assume the length of the assignment process equal to the number of time slots in a superframe, which is $n_s = 240$.

We fist run the simulation where each WRAN is overlapped with all the other WRANs, as shown in fig.4. This means that a single WRAN can transmit in each slot. This is equal to assert that in the simulation we have to consider 8 available possibilities, where each possibility is only constituted by one WRAN. The considered possibilities among which the coordinator can choose are (1),(2),(3),(4),(5)(6),(7),(8). The other parameters chosen for the simulation are: the number of WRANs $N = 8$ and $n_s = 240$. In fig.5 the number of required slots, is represented by a blue curve, while the number of assigned slots is represented by a red curve. With reference to fig.5, it is clear that, after a superframe, the curve representing the assigned slots follows the trend of the curve representing the number of required slots. In fact, the figure shows that, whether the resource are sufficient to satisfy all WRAN requests or not, the assigned slots are proportional to the WRAN requests.

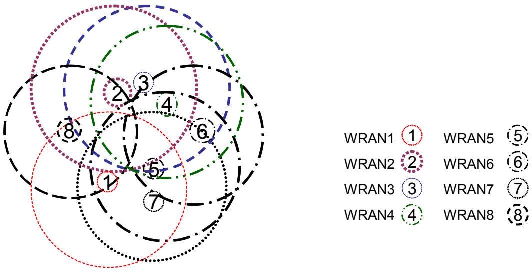

Fig. 4. Scenario with all WRANs overlapped among them

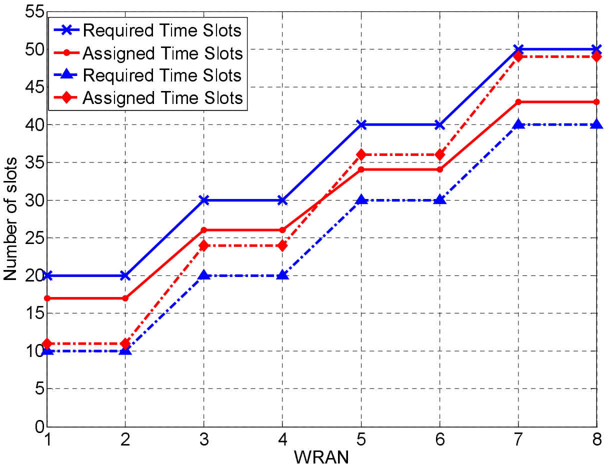

Fig. 5. Expected and real assigned number of slots in case of different p_i and 8 available possibilities

We run further simulations referred to the scenario in fig.1. We run simulations varying the number of available channels. When only a channel is available we suppose that it can be accessed by all the WRANs. When we consider two channels, we refer to the scenario of fig.1, where $channelA$ is available for all the WRANs and $channelB$ only for $WRAN2-3-4$. The chosen parameters for the simulations are: the number of WRANs $N = 5$ and $n_s = 240$. In the simulations we assume that all WRANs need the same number of time slots, which is 120, i.e. the vector of p_i becomes $[\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}]$. The results are shown in fig.6. Through simulation results, it is possible to make some observations.

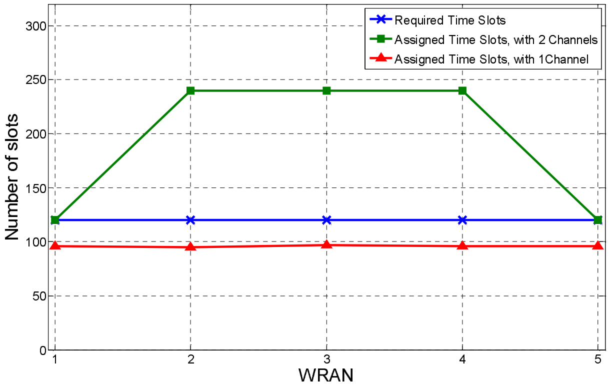

Fig. 6. Assigned slots in case of equal probabilities p_i, for 5 $WRANs$

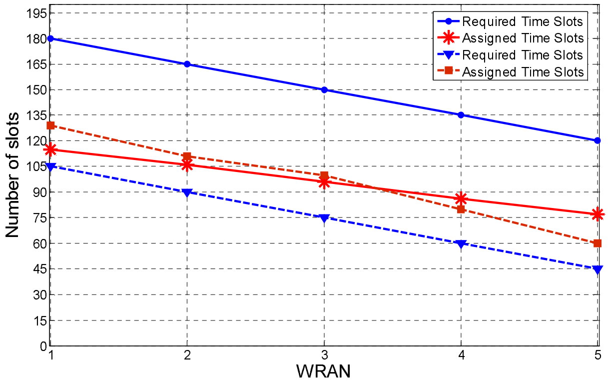

Fig. 7. Assigned slots in case of different probability p_i, for 5 $WRANs$

- As the number of available channels increases, also does the number of assigned slots. The total number of time slots assigned to a WRAN cannot exceed the length of assignment process, which is 240 slots. The reason is that using the introduced method, it is not allowed that a WRAN has more than one slot on different channels at the same time.
- Starting from the consideration that all the WRANs have the same band request, when one channel is available, the WRAN requests are equally satisfied, even if the assigned slots are less then requested. On the other side, when two channels are available, all the requests are satisfied. The WRANs covered by two channels are assigned 240 slots, instead, the WRANs covered by one channel, are assigned exactly the required number of time slots. This happens because the algorithm schedules the WRAN transmission so that $WRAN2-3-4$ use the most $channelB$ leaving the $channelA$ more available to $WRAN1-5$.

This proves the fairness of the introduced method, because also if not all the WRANs are able to utilize the same number of channels, the coordinator tries to satisfy the BS requests in the same way. In fact the algorithm does not disadvantage the WRANs that cannot use all the channels, but it tries to satisfy the WRAN requests, according to the WRAN p_i and the available $opportunities$.

Other simulations were run varying the probability vector and considering the required number of slots not equal among them. We assume they have decreasing values, respectively in the range $[180, 120]$ and $[105, 45]$, with a 15 slot step. The corresponding vectors of p_i are $[0.24, 0.22, 0.20, 0.18, 0.16]$, and $[0.28, 0.24, 0.20, 0.16, 0.12]$. The scenario we are referring to is the same of fig.1, and the duration of the assignment process is 240 time slots. In fig.7 the simulation results are shown, when a channel is available. In fig.7 the red curves depict the number of slots really assigned to each WRAN, while the blue ones show the number of required time slots. The trend of the blue curves follows the red curves.

In conclusion, we can state that the proposed algorithm allows the coordinator to schedule the WRAN transmission in such a way to guarantee a resource assignment proportional to the WRAN requests.

V. CONCLUSIONS

In this paper a resource sharing algorithm was presented, which allows the optimized distribution of resources among WRANs of a cognitive 802.22 network. The appropriate context for using the algorithm is a scenarios where there are many overlapped WRANs, which share one o more available channels.

The channel assignment process is made in such a way to allow simultaneous communications among WRANs without causing interference. Furthermore, the algorithm is able to take into account the QoS requests of WRANs, giving more bandwidth to WRANs with higher demand. We built a Matlab simulation tool to test the resource sharing method. Performance evaluation proved that the introduced algorithm assigns the time slots according to the WRAN requests.

REFERENCES

[1] C. Cordeiro, K. Challapali, D. Birru, and S. Shankar, "IEEE 802.22: The first worldwide wireless standard based on cognitive radios," in *Proc. of the First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, (DySPAN'05)*, Nov. 2005, pp. 328 – 337.

[2] H. Wendong, M. Gerla, G. Vlantis, and G. Pottie, "Efficient, flexible, and scalable inter-network spectrum sharing and communications in cognitive IEEE 802.22 networks." First International Workshop on Cognitive Radio and Advanced Spectrum Management, Feb. 2007.

[3] R. Chen, L.Weiying, and L. Jiandong, "Auction-based inter bs spectrum sharing for IEEE 802.22 WRAN systems," in *Proc. of the 4th IEEE Conference on Industrial Electronics and Applications (ICIEA 2009)*, May 2009, pp. 1787 – 1791.

[4] H. Wendong, D. Willkomm, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz, "Cognitive radios for dynamic spectrum access-dynamic frequency hopping communities for efficient IEEE 802.22 operation," *IEEE Communications Magazine*, no. 45, May 2007.

[5] S. Brahma, M. Chatterjee, and N. S. Shankar, "Enhancements to cognitive radio based IEEE 802.22 air-interface," in *IEEE International Conference on Communications (ICC '07)*, Jun. 2007, pp. 5155 – 5160.

[6] M. G. C. Cordeiro, K. Challapali, "Cognitive PHY and MAC layers for dynamic spectrum access and sharing of TV bands," in *IEEE International Workshop on Technology and Policy for Accessing Spectrum*, 2006.

[7] S. Hwang, J. S. Um, M. Song, C. Kim, H. Park, and Y. Kim, "Design and verification of IEEE 802.22 WRAN physical layer," in *Cognitive Radio Oriented Wireless Networks and Communications*, 2008.

[8] S. Benedetto, E. Biglieri, and V. Castellani, *Digital Transmission Theory*. Prentice Hall, 1987.