

Cognitive Radio using Spectrum-Sharing and Power Minimisation

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Abstract— In this paper, we use a Spectrum Sharing/allocation algorithm to implement a Cognitive Radio network without spectral awareness. This allows radio resources to be allocated to primary users and to secondary users in such a way that primary system and secondary system are aware of each other. By doing this, sensing of spectrum holes is avoided but the primary users will be protected and will always be allocated sufficient bandwidth to meet their QoS requirements. However, secondary users also have the concept of QoS and only those that can be given *sufficient* resources are actually allocated any, so avoiding wasting resources on users that cannot meet their QoS requirements. The scenario adopted is a multi-cell OFDMA network and the resource allocation is formulated as a non-cooperative game: each cell is a player whose aim is to maximise the number of secondary users that can reach their bitrates subject to the premise that all primary users in that cell can achieve their bitrate. Once spectrum is allocated we implement a power-minimisation algorithm to minimise the power consumption in the network while maintaining the number of users meeting their QoS requirements. Simulation results show the benefit of the approach.

Keywords—cognitive radio; spectrum sharing; game theory

I. INTRODUCTION

The concept of cognitive radio (CR) is that it allows secondary users (SUs) to sense the “spectrum holes” of the primary spectrum in the time, space and frequency domains in an autonomous manner and then make rational use of them in an opportunistic way on the premise of causing limited and tolerable interference to primary users (PUs). The spectrum hole is a band of frequencies assigned to a PU, but, at a particular time and specific geographic location, the band is not being utilised by that user [1]. This is attractive because it avoids wasting spectrum that is allocated but unused at that time.

The detection of the holes requires spectrum sensing and although a lot of research has been done on CR, sensing is still a problem. To provide rapid and reliable sensing results in all circumstances is difficult and sensing is one of the key factors influencing the development of CR and in [2], problems that still need to be solved are identified: problems like low SNR sensing, hidden node problem, QoS guarantee, passive device detection and challenges in wideband spectrum sensing.

This concept of allowing SUs to transmit in the holes is termed *overlay spectrum sharing* [2] (or Opportunistic Spectrum Access (OSA) or Dynamic Spectrum Access (DSA)) and is illustrated in Fig. 1.

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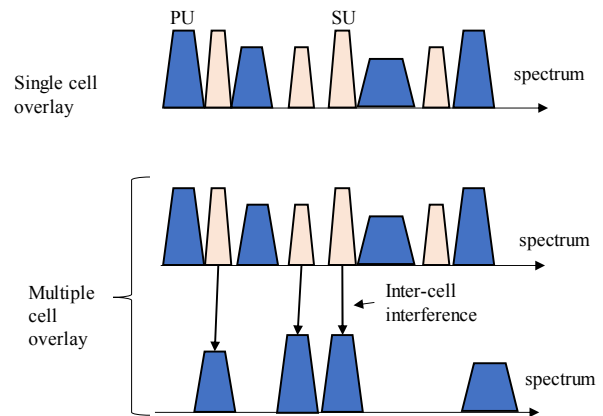


Fig. 1 Overlay spectrum sharing

The overlay spectrum sharing gives PUs the highest priority on occupying the spectrum and SUs are only allowed to use unused spectrum where there is an absence of PUs so they must employ spectrum sensing and keep monitoring as the occupied spectrum must be released if a PU starts using it. In the IEEE Standard 802.22 this is provided by either a geo-location database or by spectrum sensing [3].

However, as also shown in Fig. 1, the situation is much more complex when more than one cell is considered because an SU can easily generate inter-cell interference (ICI) to a PU in an adjacent cell, especially when the cell radius is small. Although a lot of work on CR assumes a single cell model (e.g. [4], [5]) the demand for increasing bandwidth by users means that a multi-cell structure is better for providing the required capacity in a denser population area.

Underlay spectrum sharing applies spectrum spreading to the SU's signal in order to spread the transmit power over an ultra-wide spectrum so that the transmit power is very low and the interference from the SUs to the PUs does not exceed a certain threshold [6]. Underlay is not considered in this paper.

In [7], the authors proposed spectrum as a basis for joint power/channel allocation to improve network performance. In [8] we proposed a multi-cell CR network that aims to always satisfy PUs, without SUs having to pay attention to the PUs at the expense of sacrificing the transparency of SUs to the PUs. Such a network requires no sensing hardware as resource allocation is managed across all users and the division between

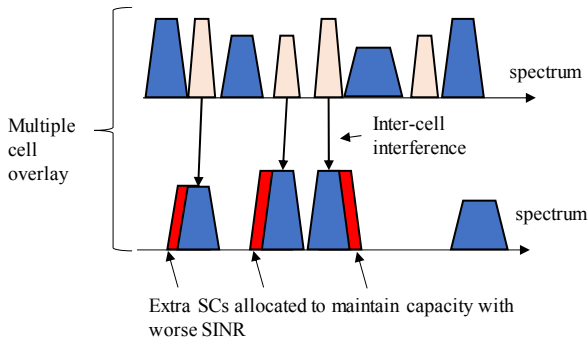


Fig. 2 Mitigating the effect of ICI on PUs

PUs and SUs can be based on the service provider to which they belong, or to different priorities between users for the same service provider.

Orthogonal Frequency Division Multiple Access (OFDMA) is assumed as the multiple access technique for CR. OFDMA distributes a set of orthogonal subcarriers (SC) to individual users and the orthogonality ensures SCs generate no interference to others within the cell. By applying OFDMA to remove intra-cell interference in this way, the ICI becomes the dominant interference source as illustrated in Fig. 1.

Applying sensing to detect holes across multiple cells corresponding to spectrum desired by SUs would be a very complex process, so the approach adopted in [8] was to consider resource allocation to all users, but to ensure PUs had absolute priority to receive sufficient resources to meet their QoS requirements.

We use the capacity (in the Shannon-Hartley sense) as a proxy for the QoS and the bandwidth allocated (i.e. number of SCs) as the input needed to achieve that capacity, depending on the SINR seen by that user. Hence, if a SU causes more interference to a PU, it is better to allocate more SUs to the PU as shown in Fig. 2 than stopping the SU transmitting.

The *principle* of taking that approach to CR was demonstrated in [8], but in this paper, we consider the performance of this fully-cooperative scheme with the inclusion of power minimisation.

II. OVERALL CONSIDERATIONS

Fig. 3 shows two different approaches to sharing a common pool of spectrum: (a) has one pool of spectrum and both operators share the same transmission equipment; in (b) the same pool of spectrum is made available to the base stations of both operators. Logically these are the same so this paper will assume (a) as the calculation of the interference map for (b) is much more complex.

With CR, secondary users opportunistically use the vacant spectrum of primary users and this is classified as orthogonal spectrum sharing [7] as that is where, in any given area, no operator can be allocated a frequency that is already in use by another.

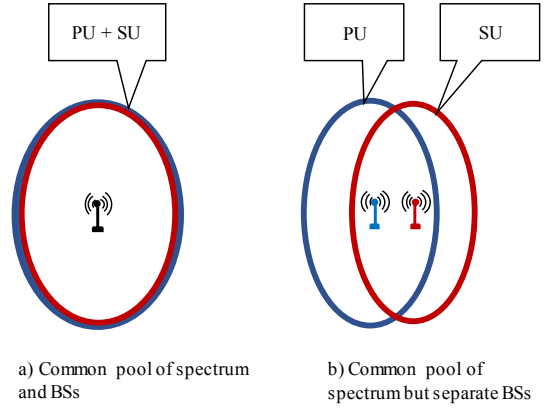


Fig. 3 Sharing a pool of spectrum

For user satisfaction, users must acquire the necessary QoS to support their applications – if the QoS is too low then their experience will be degraded and if too high then the system will waste resources. Our aim is not to maximize the overall throughput but to maximize the number of users that receive their minimum QoS requirement – we term those users *Qualified Users*. It is important to note that we extend this concept to secondary users as well.

There are two types of spectrum sharing: (i) cooperative and (ii) non-cooperative [6]. Cooperative spectrum sharing occurs when the nodes accept negotiation and coordination to achieve a common goal; they usually belong to the same service provider. Non-cooperative spectrum sharing allows the nodes to try to gain the most, regardless of the influence of their actions on the others. The nodes are rational and selfish so that they have no concern about the effect of their behaviour on each other and only a minimal information exchange is required between them. This form of sharing exists on distributed network [6] and is the form used here.

To implement the spectrum sharing, game theory is used. Game theory has been widely used in modelling the spectrum sharing problem for CR, for example [7], [9], [10] and [11]. In [12], the authors took the BSs as players and the number of subscribers as the utility function. Here we take the BSs as players but the number of *qualified* users as the utility function and we add the constraint that as many as possible of the PUs should be qualified before considering adding SUs.

III. PROBLEM FORMULATION

A. Overall approach

Our approach is different from that in [7] as there the authors allowed the transmission power to be selected by users as part of the game with a user-dependent pricing scheme and control-packet exchanges. Here we separate the resource allocation and power control.

- i) Resource allocation is performed with transmission powers maximised. The allocation is implemented using game theory. Both PUs and SUs are allocated radio resources to allow them to become qualified users: i.e. to have sufficient allocated for them to meet their QoS requirements. As part of this process, the

algorithm ensures that all PUs become qualified users before SUs receive any resources. This meets the high-level objective of CR in that SUs only use resources where that does not interfere with PUs.

- ii) Following the resource allocation, a process is carried out to minimise the transmission power of each user, subject to the constraint that a minimum received power must be seen at the receiver. Again, in this process PUs are protected so that no PU that was qualified becomes unqualified.

It would be possible, of course, to combine these steps with into a multi-objective optimisation problems with the variables being RB allocation and transmission power. Methods for solving such problems included the weighted sum method [13] where the individual objective functions are combined. However, Marler and Arora in [14], following a very comprehensive survey of multi-objective optimisation methods, concluded that the solution of several *single* objective problems may be necessary and such separation is adopted here.

B. Resource allocation

1) Game structure

Non-cooperative game theory is used to allocate radio resources in this research for three reasons:

- With the model of Fig. 3(a), a BS allocates radio resources independently of other BSs. In this way it acts as a selfish independent player maximising its own profit while competing with other BSs that have the same non-cooperative behaviour.
- There is no need for signalling between BSs.
- Game theory offers reasonably fast convergence and can be easily applied in practice (although it might lead to a suboptimal solution [15]).

In this paper, a static scenario is considered, although non-static can be handled through a sequence of snapshots. The PUs and SUs request radio resources (that, for generality, here are termed resource blocks, RBs) from BSs in a multi-cell OFDMA network. Each BS runs a game-theory algorithm and assigns the RBs to the users within its coverage. Non-cooperative game theory is suitable for modelling this type of multi-person problem characterised by strategic interdependency [16], although the solution may be suboptimal [15].

The utility of each cell depends not only on its own decision but also the decisions of the other players because of the inter-cell interference (ICI) - the allocation of RBs will cause co-channel interference to neighbouring cells so improvement in one cell may degrade the performance in an adjacent one. By observing the channel conditions from round to round, the BSs change their RB allocation decisions until all the cells choose to stick to their current decisions and equilibrium is reached.

Here the non-cooperative game G is formed by three essential elements: *players*, the *action space* and the *utility function*.

- i) The *players* are the K BSs each containing I_k users. The literature often considers users as players but that is where only one cell is being optimized: with OFDMA the

interference is inter-cell so the interaction between cells is best handled by making the BSs the players.

- ii) The *action space* is the combination of all possible RB allocation schemes of all players denoted as $\{p_{k,i}(m)\}$ where $u_{k,i}$ is the i^{th} user of cell k and $p_{k,i}(m)$ is the power at the receiver transmitted by user $u_{k,i}$ on RB m subject to $p_{k,i}(m) = 0$, if $u_{k,i}$ does not use m .
- iii) The *utility function* is maximised on a per-cell basis and is the number of qualified users in that cell, q_k .

2) Qualified User Ratio

The measure to determine whether a user is qualified is the capacity (in the Shannon-Hartley sense) available to that user. Capacity is used because (i) transmission rate is the most important factor influencing the perceived quality of video streaming and (ii) video streaming is probably the most common high bitrate service. Capacity also fits the principle of OFDMA where blocks of bandwidth (RBs) are allocated.

The relationship between capacity C and bandwidth B can be determined using the Shannon-Hartley equation. Let $\{S_{k,i,j}\}$ be the set of signal powers at the receiver corresponding to $u_{k,i}$ where $\{j\}$ is the set of RBs allocated to that user and $N_{k,i,j}$ is the received noise+interference power. Assuming the bandwidth of each RB is identical we get:

$$C_{k,i} = \sum_j B \log_2 \left(1 + \frac{S_{k,i,j}}{N_{k,i,j}} \right) \approx \frac{B}{3} \sum_j \text{SINR}_{k,i,j} \quad (1)$$

This uses the well-known approximation of the Shannon equation where SINR is the ratio (in dB) of signal power to the power of noise plus interference. Since this approximation is linear it is possible to estimate the capacity available to a user by adding the capacities for each RB allocated to that user; this generates the sum of SINRs (sSINR). This approximation is used only to allocate RBs; calculation of the interference map and capacity is based on the full Shannon equation.

The problem formulation is hence to maximize the qualified user number, i.e. maximise those users whose capacity exceeds their requested minimum value, which can be specified independently for each user, although in this paper it is assumed that each user requests the same bandwidth.

Assuming the interference is only that co-channel interference generated by neighbouring cells we get:

$$C_{k,i}(m) = \frac{h_{k,i}^k(m)p_{k,i}(m)}{N(m) + \sum_{k' \neq k, k' \in K} \sum_{i \in I} h_{k',i}^{k'}(m)p_{k',i}(m)} \quad (2)$$

where $h_{k,i}^k(m)$ is the channel gain of user $c_{k,i}$ to BS k on RB m and $N(m)$ is the Gaussian noise on RB m .

Constraints are added to the utility function as follows:

- i) The total transmission power of a single user cannot exceed a maximum value specified in the standards, $p_{\max}$.

- ii) In any cell a particular RB can only be allocated to one user so that there is no reuse of RBs between sectors.

3) Algorithm structure

The steps are as follows and explained in more detail in [8]:

- i) **Initial prioritised SC allocation.** The BSs allocate RBs to users in order of decreasing distance from the centre of the cell. Each user must be allocated sufficient RBs to be qualified, but as there is no interference information available at this stage, we use a target sSINR that is slightly above the minimum to allow for the interference.
- ii) **RB release:** calculate the sSINR of each user and release the RBs allocated to those users that do not have a good enough sSINR to achieve their QoS.
- iii) **PU compensation:** compensate any unqualified PUs to achieve their minimum sSINR by allocating more RBs. If insufficient vacant RBs are available, SUs release RBs to make them available to PUs.
- iv) **RB reallocation:** Following PU compensation, the BSs reallocate unused RBs to unqualified users. This process is carried out iteratively with RB release after each round as some users may be qualified under the current interference pattern but become unqualified as the interference changes.

Steps (ii)-(iv) are repeated in a loop, with the interference map being recalculated at each loop until the RB allocation result converges or the maximum iteration value is reached.

The key protection for the PUs, an essential requirement for a CR network, is through two features:

- i) PUs have highest priority in choosing RBs and take precedence over the distance priority, so no matter where the PUs are located they will always have the first choice.
- ii) The PU compensation mechanism is specially designed to turn unqualified PUs to be qualified for that iteration, even with the risk of decreasing the system capacity.

C. Power Consumption

Power reduction can be structured as a Game but it is possible to simplify the process because none of the users is actually competing against any other as reducing the power to a user reduces the co-channel interference and hence improves the SINR for users allocated that RB in adjacent cells – no user is adversely affected. The total power is minimised by minimising the power to each qualified user subject to the constraints:

- i) That each qualified user remains qualified – i.e. that it still has sufficient sSINR to meet the QoS objective.
- ii) The received power at the BS, $p_{k,i}^R$ on RB m for user $u_{k,i}$, must be $\geq p_{min}^R$ for satisfactory detection.

The power reduction is initialised by calculating the interference map and the sSINR for each qualified user using the RBs already allocated, with the power on each RB set to be the maximum transmit power for an RB: p_{max} . Note that unqualified users have power set to 0 with no RBs allocated and that, for any given user, the power on each RB is the same.

The overall approach then runs as follows for each user:

- i) Calculate the transmit power required to reduce the sSINR to the minimum for the user to remain qualified and the corresponding received power.
- ii) Check whether the received power satisfies the receive power constraint p_{min}^R .
- iii) If the receive power would be sufficient, use this value of transmit power for the next loop, using the worst value of channel gain for the RBs allocated to that user.
- iv) If the receive power is insufficient set the transmission power as being that which would give the minimum receive power (again using the worst value of channel gain) and compare with p_{max} .
 - o If $\leq p_{max}$ then use this value for the next loop..
 - o If $> p_{max}$ then use p_{max} for the next loop. This is a possible consequence of using the worst channel condition for all RBs allocated to a user.

When all users have been considered, calculate the new interference map using the new transmit powers and loop until convergence is reached.

A user may have been allocated several RBs, each with different channel conditions, so there is another optimisation problem on how to reduce the power to each RB separately. Here that is simplified by assuming that (i) the transmit power for each RB is the same and (ii) that the worst channel condition is used for all RBs. This will not lead to the lowest possible power but is conservative in that the sSINR will actually be a bit higher than the minimum.

IV. SYSTEM MODEL

OFDMA uplink transmission is considered. Each 3-sector BS is located in the centre of every cell and is assumed to have full knowledge of the channel quality information of the users in that cell. The system parameters are shown in TABLE I.

TABLE I. MAIN SYSTEM PARAMETERS

Parameter	Value
Modelling scenario	Suburban with 7 cell cluster
User distribution	Uniform
Central frequency	300MHz
RB bandwidth	120kHz
Number of RBs per cell	90
TX power per RB p_{max}	23dBm ($\approx 0.2W$)
Max number of RBs per user	5
Shadow fading	log-normal ($\sigma=8dB$)
Cell Radius (r)	2km
Path loss	COST231-Hata
Antenna gain	12dBm
User's bitrate requirement	1Mbps
Minimum sSINR to be qualified	25dB
p_{min}^R (receiver threshold)	-110dBm
Ratio of PU:SU	1:3

V. RESULTS

These results are the average from conducting 50 runs using a different random seed for each run.

In Fig. 4 we show that the approach is working properly as a CR network in that the qualified user ratio remains at 1 for PUs (i.e. all PUs are qualified), even as the number of users in the system increases. However, as the number of users increases beyond about 180, the system cannot handle all the users so the QUR for SUs decreases as SUs are increasingly sacrificed in favour of PUs.

It is important to note that the QUR is unaffected by the power reduction. In this case the results with 25 loops of power reduction are identical to those without so the separation of the utility functions has not affected the system capacity.

The power reduction is illustrated in Fig. 5. The solid lines (related to the left-hand axis) compare the total power used with no reduction (0 loop) against that after 25 loops of reduction. The dotted line (right-hand axis) shows the percentage reduction in power and that is of the order of 80% when the system is saturated – i.e. it is having to sacrifice SUs to maintain the PU QUR.

Importantly Fig. 6 shows sSINR before and after power reduction: as the number of users increases and all the RBs are in use, the sSINR asymptotically approaches the target sSINR of 25dB demonstrating the power reduction is effective at removing “waste” from the system: excess sSINR above the target is effectively wasting power.

Together, these results demonstrate that the process is effective and that using the maximum transmission power for the resource allocation does not adversely affect the overall outcome.

Small points to note are (i) that the power reduction is greater for a small number of users as there is little interference in such circumstances (which is why the sSINR is above the target for a lightly loaded system) and (ii) the power reduction will fluctuate a little, even over 50 runs, depending on the actual distribution of users as more edge users will mean more power is required.

In these results so far, the power reduction has been accomplished by considering PUs and SUs together. However, it is possible to treat them separately and the results of such a

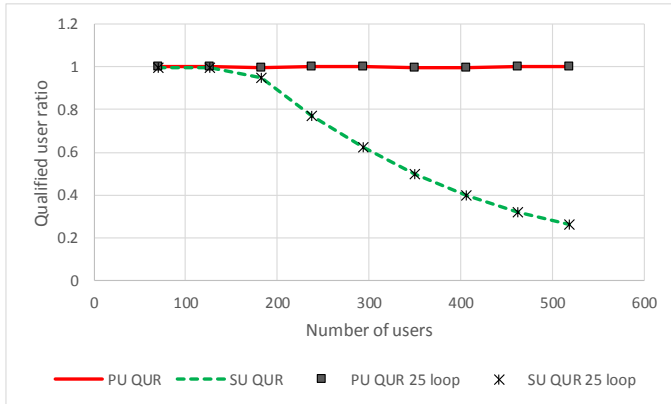


Fig. 4 Qualified User Ratio – without and with power reduction

separation are shown in Fig. 7 and are compared with joint approaches used for Fig. 5 and Fig. 6 for 518 users.

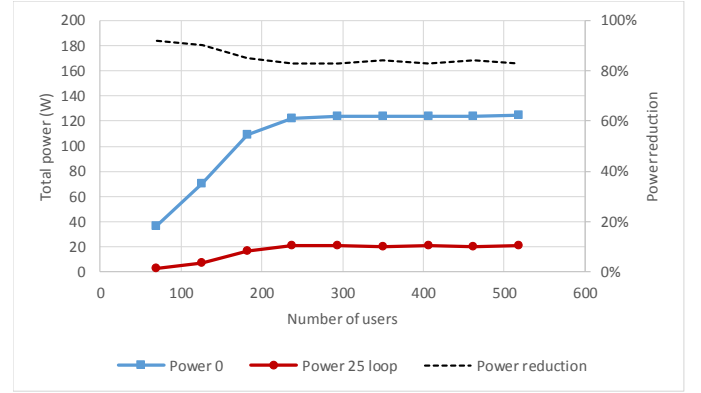


Fig. 5 Power vs no of users before and after power reduction

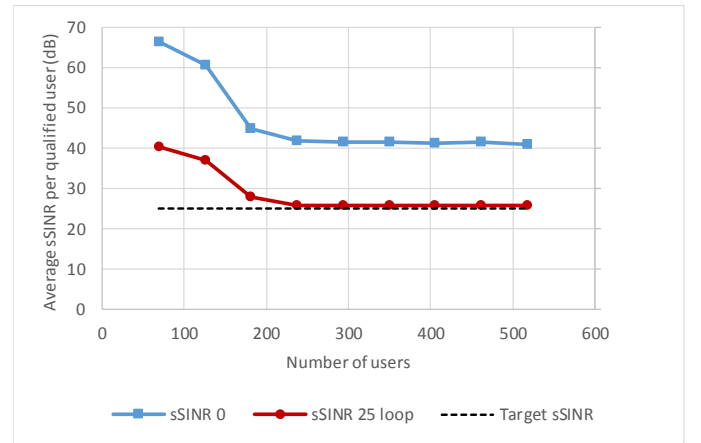


Fig. 6 sSINR vs no of users before and after power reduction

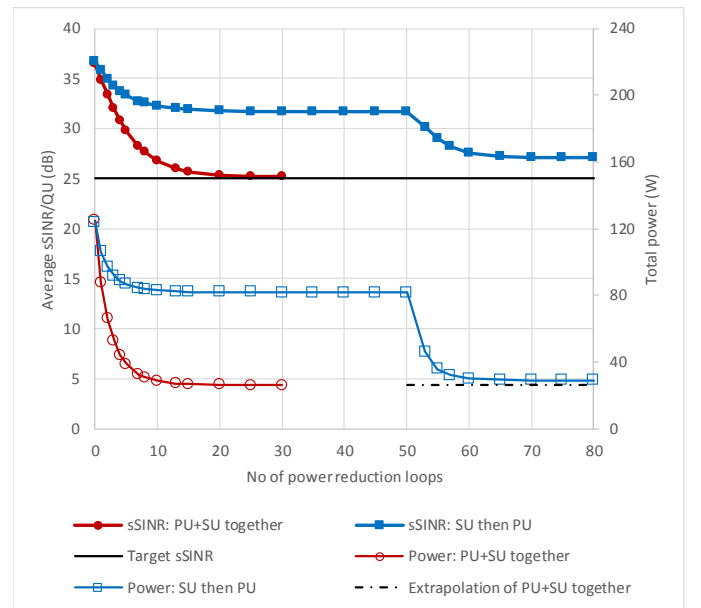


Fig. 7 Comparison between joint power reduction and separate

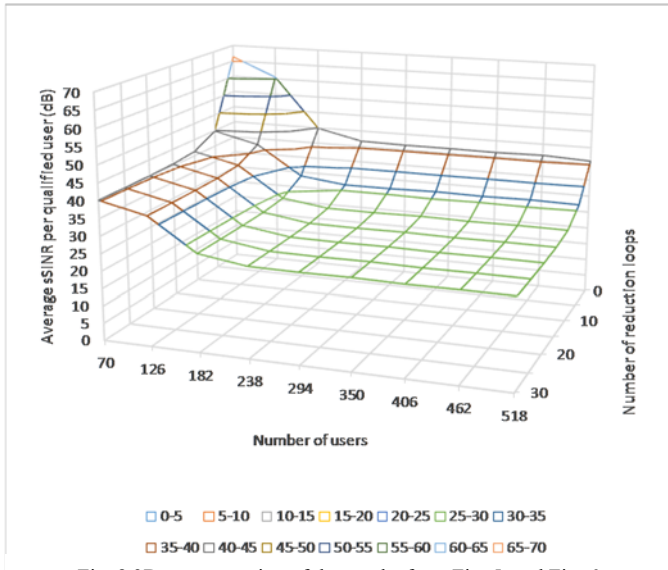


Fig. 8 3D representation of the results from Fig. 5. and Fig. 6.

The lines with circular markers show the same results as in Fig. 5 and Fig. 6, except instead of being against user number they are against loop. The square markers indicate a process that runs power reduction on all the SUs first without affecting the power of PUs. This reduces the interference seen by the PUs and subsequently the power reduction process is run on the PUs only. Although the results show that there is good overall reduction, it is clearly not quite as good as treating all users at the same time. This reinforces the principle of the whole approach that benefit is obtained overall by treating PUs and SUs together, not just allocating resources to PUs and then filling the gaps with SUs.

In this process there are two variables: the number of reduction loops and the number of users. To get an indication of the sensitivity of the algorithm the results used for Fig. 5 and Fig. 6 are shown in a 3D representation in Fig. 8. Note that number of reduction loops is plotted in decreasing order as this shows the 3D representation more clearly.

These results show that there a large part of the area has achieved an sSINR close to the target value – essentially for all area from saturation of the system and beyond about 10 loops.

VI. CONCLUSIONS

In this paper we demonstrate the effectiveness of applying spectrum sharing to CR networks and managing the resources across PUs and SUs at the same time: not only does the approach give absolute priority to PUs over SUs, it allows significant power reduction to take place without affecting the qualified user ratio. This takes place even though the initial transmit power for the resource allocation phase was set to maximum.

Significant power reduction can, therefore, take place without having to have some sort of weighting to combine the resource allocation and power utility functions, nor for the need for any pricing mechanism to be built into the approach.

It is also clear from the results that the reduction is close to optimum as the sSINR falls asymptotically to the target value.

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REFERENCES

- [1] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, 2005.
- [2] H. Venkataraman and G.-M. Muntean, Eds., *Cognitive Radio and Its Application for Next Generation Cellular and Wireless Networks*, Springer, 2012, pp. 29-93.
- [3] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer and W. Caldwell, "IEEE802.22: The first Cognitive Radio wireless regional area network standard," *IEEE Comms. Mag.*, vol. 47, no. 1, pp. 130-138, January 2009.
- [4] S. Bhattacharjee, A. Konar and A. Nagar, "Channel allocation for a single cell cognitive radio network using genetic algorithm," in *Innovative mobile and internet services in ubiquitous computing (IMIS), 2011 fifth international conference on*, 2011.
- [5] E. A. Gharavol, Y.-C. Liang and K. Mouthaan, "Robust downlink beamforming in multiuser MISO cognitive radio networks with imperfect channel-state information," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 6, pp. 2852-2860, 2010.
- [6] V. U. Kanth, K. R. Chandra and R. R. Kumar, "Spectrum sharing in cognitive radio networks," *International journal of engineering trends and technology*, vol. 1, no. 4, pp. 1172-1175, 2013.
- [7] F. Wang, M. Krunz and S. Cui, "Spectrum Sharing in Cognitive Radio Networks," in *INFOCOM 2008. The 27th Conference on Computer Communications.*, 2008.
- [8] Y. Liu, L. Cuthbert, X. Yang and Y. Wang, "QoS-aware Resource Allocation for Multimedia Users in a Multi-cell Spectrum Sharing Radio Network," in *Proceedings of the 7th ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks*, Paphos, 2012.
- [9] Y. Wu and D. Tsang, "Distributed Multichannel Power Allocation Algorithm for Spectrum," in *IEEE Wireless Communications and Networking (WCNC)*, 2008.
- [10] D. Niyato and E. Hossain, "Competitive spectrum sharing in cognitive radio networks: a dynamic game approach," *IEEE Transactions on Wireless Communications*, vol. 7, no. 7, pp. 2651-2660, 2008.
- [11] R. Etkin, A. Parekh and D. Tse, "Spectrum Sharing for Unlicensed Bands," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 517-528, 2007.
- [12] G. Hosseinabadi, M. H. Manshaei and J.-P. Hubaux, "Spectrum sharing games of infrastructure-based cognitive radio networks," *École Polytechnique Fédérale de Lausanne, Lausaane*, 2008.
- [13] K. Deb, *Multi-objective optimization using evolutionary algorithms*, John Wiley & Sons, 2001.
- [14] R. Marler and J. Arora, "Survey of multi-objective optimization methods for engineering," *Structural and Multidisciplinary Optimization*, vol. 26, no. 6, pp. 369-395, 2004.
- [15] K. R. Liu and B. Wang, *Cognitive Radio Networking and Security: a Game-Theoretic View*, Cambridge University Press, 2010.
- [16] I. Aguirre, "Notes on Non-Cooperative Game Theory - Microeconomic Theory IV," *Universidad del País Vasco*, 2009. [Online]. Available: <http://www.ehu.es/iaguirre/MicroIVEnglish/NotesGames2009.pdf>. [Accessed 10 January 2017].