

Self-organizing dynamic spectrum management for cognitive radio networks

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Abstract—Dynamic spectrum management (DSM) is one of the key problems in the design of cognitive radio (CR) networks. It is a time-varying and location-dependent optimization problem, equivalent to the well-known graph-colouring problem in graph theory. This problem is known to be NP-hard and computationally challenging to solve. Accordingly, finding the exact solution for the DSM optimization problem is typically not practical. In this paper, we introduce a novel self-organizing DSM scheme, which solves the DSM problem in a decentralized manner. The use of self-organization to address the DSM problem offers several benefits: decentralization and scalability of the network behaviour, computational simplicity, cost-effectiveness and bandwidth conservation. In the paper, we address the underlying principles involved in the design and implementation of the self-organizing DSM as well as a software testbed for demonstrating this novel approach. Experimental results are presented to justify this new approach.

Keywords—Cognitive radio, Dynamic spectrum management, Self-organizing maps.

I. INTRODUCTION

The electromagnetic radio spectrum is a natural resource, licensed and carefully managed by governments to ensure secure and reliable wireless communication. With wireless communications becoming increasingly pervasive all over the world, people are more frequently using wireless devices and services, and there is a growing demand for high-speed wireless communications. Nowadays, various devices such as laptops and cell phones require high-speed wireless services; and ever so frequently, a new device or application is developed which requires broad-band wireless communication. A key question that arises is then: How do we cater to this continuing growth of wireless devices and services, given that the radio spectrum is of limited extent?

Currently, the radio spectrum is managed in a static way, that is a wireless service provider buys the license for one or some spectrum bands and only its users, termed *legacy* or *primary* users (PUs), are allowed to operate in these bands. Therefore, radio units are designed to operate only on those specific bands and are sure that no other radio will interfere with them. For example, the GSM-900 network uses 890-915 MHz and 935-960 MHz bands, and

the 108-138 MHz band is reserved for air traffic control [1]. Spectrum management using this *static* policy is simple and easy to implement; however, recent studies [2] have shown that it needs to be reviewed and modified for two reasons:

- 1) The operable spectrum band is limited due to system design and implementation issues. The operational spectrum band for current commercial wireless systems ranges from 0.4 GHz to 6 GHz and most of this band is already reserved. Therefore, in the near future there may well be no room left for fast-developing new applications.
- 2) Efficiency of the current spectrum management policies is low, resulting in under-utilization of this limited and highly valuable resource. For example, measurements performed in [3] have shown that from January 2004 to August 2005, on average, only 5.2% of the radio spectrum was actually in use in the United States.

Accordingly, although the operational band is getting slowly wider, as new technologies increase the operational requirement bandwidth of new devices, we need to increase the spectrum utilization efficiency in order to serve the fast-growing demand for broadband wireless communications.

A. Cognitive radio

Cognitive radio (CR) is fast emerging as a way of responding to under-utilization of the radio spectrum. For a working definition of cognitive radio, we offer the following [4], [5]: The cognitive radio network is an intelligent multi-user wireless communication system that embodies the following list of primary tasks:

- to perceive the radio environment (i.e., outside world) by empowering each user's receiver to sense the environment on a continuous-time basis;
- to learn from the environment and adapt the performance of each transceiver to statistical variations in the incoming RF stimuli;
- to facilitate communication between multiple users through cooperation in a self-organized manner;
- to control the communication processes among competing users through the proper allocation of available

resources; and

- to create the experience of intentions and self-awareness.

The primary objective of all these tasks, performed in real-time, is two-fold:

- to provide highly reliable communication for all users wherever and whenever needed; and
- to facilitate efficient utilization of the radio spectrum in a fair-minded way.

The operation of cognitive radio hinges on the availability of *spectrum holes*, under-utilized frequency bands of the radio spectrum, owned by legally licensed (primary) users; they are formally defined as follows [4]:

A spectrum hole is a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not being utilized by that user.

The identification and exploitation of spectrum holes presents technical challenges grouped under two categories, one rooted in computer software, and the other rooted in signal processing and communication technology. These technical challenges are further compounded by the fact that the spectrum holes come and go in a stochastic manner.

This paper introduces a novel decentralized dynamic spectrum scheme, termed self-organizing DSM (SODSM) for cognitive radio networks. In Sec. II, dynamic spectrum management in a cognitive radio network is explained. Next, we introduce a self-organizing dynamic spectrum management scheme in Sec. III. In Sec. IV, our software testbed and network model are explained and simulation results are presented. Finally, the paper concludes in Sec. V.

II. DYNAMIC SPECTRUM MANAGEMENT (DSM)

Dynamic spectrum management assigns the available spectrum holes among the CR units according to the environmental constraints and is one of the main challenges in cognitive radio [4], [5]. Cognitive radio units try to increase the spectrum utilization efficiency by sensing the environment, detecting the spectrum holes and using them as long as they are not used by a primary user. When two CR units need to communicate and establish a link, the DSM subsystem chooses one of the common spectrum holes between them and they operate on that band as long as it is available. If during communication, a primary user is detected on that band, the transmitter CR unit must stop transmission *immediately* and find another common spectrum hole to use. Mathematically, the DSM problem is equivalent to the well-known graph colouring problem in graph theory [6]. Figure 1 illustrates a simple CR network scene and its equivalent graph. In Fig. 1(a), there are 11 CR units from which 5 pairs, connected with solid lines and named l_1, l_2, \dots, l_5 , require to establish

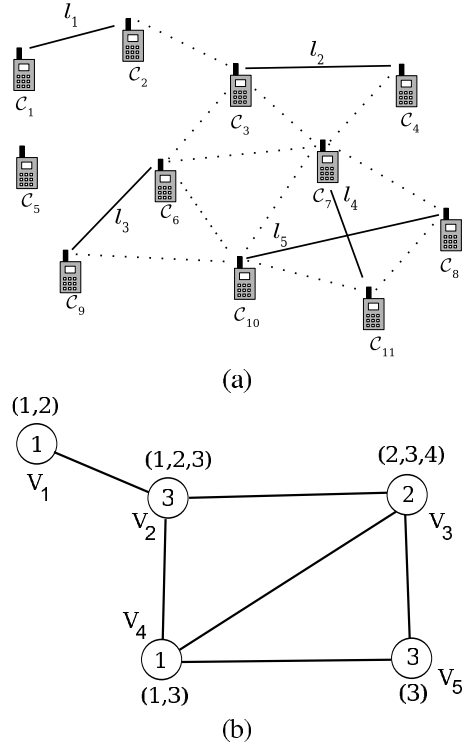


Figure 1. (a) A DSM scene with 11 CR units; the solid lines represent data links between CR units and dotted lines represent interference between two CR units. (b) The graph representation of (a) where each vertex represents a link and available channels for each link is shown on its corresponding vertex. One possible solution is also shown by channel numbers in the vertices.

a data link. The CR units in the *interference range* of each other are connected with dotted lines. When two CR units are in interference range of each other, they can not operate on the same band simultaneously. As shown in Fig. 1 (b), in the equivalent graph, there is one vertex for each solid line i.e. link in the network and vertices having one or more CR units in interference range of each other are connected. Now using the available colours (channels), we want to colour the vertices in a way that no two connected vertices have a common colour. There is also one more constraint imposed by the primary network: for some vertices (links) some colours (channels) may not be available because they are being used by primary network. In Fig. 1 (b), each colour is represented by a number and the available colours for each vertex are printed. For example, for V_1 which represents l_1 , channels 1 and 2 are available, and for V_3 , only channel 3 is available.

There are two important issues which make the DSM problem hard to solve:

- 1) The wireless environment is highly dynamic and the problem constraints and parameters are continuously changing in time. Thus, the CR unit must be able to

perform dynamic spectrum management fast enough to follow the environmental changes.

- 2) Desirably, the DSM of each link in the network must result in an optimal channel assignment over the entire CR network; this problem is known to be NP-hard [7]–[9] and therefore computationally challenging to solve.

There are two different approaches for solving the DSM problem:

- 1) Centralized approach, in which a centre gets the radio scene information from all CR units and solves the DSM problem for the entire network.
- 2) Decentralized approach, in which CR units solve the DSM problem locally, based on their neighbourhood radio spectrum set-up.

Although centralized approaches may result in a globally optimum solution, they are not feasible for solving the DSM problem because they are computationally complex, require a computationally high capacity centre (base station) and communication between the centre and all the CR units. Decentralized approaches, in contrast, try to find a sub-optimal but still satisfactory solution based on the local interactions between CR units. In this paper, we propose a decentralized DSM scheme for CR ad hoc networks based on self-organization.

III. SELF-ORGANIZING DSM (SODSM)

Self-organizing DSM, neurobiologically motivated, assigns the spectrum holes to CR units based on self-organizing maps [10], [11]. Based on recent observations, each CR unit tries to identify the sub-bands in its local environment in which primary users are present so as to avoid using them. This scheme decreases the probability of collision with PUs while it is computationally simple and fits the requirements of the DSM problem.

A. Self-organizing Maps (SOM)

Self-organizing maps, invented by T. Kohonen [10], are a specific class of neural networks whose main goal is to adaptively transform an incoming signal pattern of arbitrary dimension into one- or two-dimensional discrete map in a topologically ordered manner [11]. The building block of the SOM is a *neuron*. The relation between input signal $\mathbf{x} = [x_1 \ x_2 \ \dots \ x_m]$ and output signal y is represented by:

$$y = \varphi\left(b + \sum_{i=1}^m w_i x_i\right)$$

where φ is the activation function and $w_1 \ w_2 \ \dots \ w_m$ are the *synaptic weights* [11]. Usually, SOM is formed from a 1- or 2-dimensional lattice of neurons. There are three essential processes required for the formation of SOM [11]:

- 1) Competition;
- 2) Cooperation;

3) Synaptic adaptation.

Using a form of *Hebbian learning*, by adjusting their synaptic weights the neurons become selectively tuned to various input patterns.

The Hebbian postulate of learning, discovered by Hebb [12], is one of the oldest learning rules. It states that biological synaptic weights' changes are proportional to the correlation between presynaptic and postsynaptic signals [11]. The learning process extracts information from the environment and stores it in the synaptic weights of the neuron. Therefore, at each step of the learning process, an appropriate adjustment is applied to each synaptic weight. We represent this adjustment for synaptic weight w_j in the n th step by $\Delta w_j(n)$, i.e.:

$$w_j(n+1) = w_j(n) + \Delta w_j(n). \quad (1)$$

A synapse that obeys Hebbian learning rule is called a *Hebbian synapse*. A more precise definition for Hebbian synapse is proposed in [11]:

A synapse uses a time-dependent, highly local, and strongly interactive mechanism to increase synaptic efficiency as a function of the correlation between the presynaptic and postsynaptic activities.

The general form of the weight adjustment for the Hebbian learning process is [11]:

$$\Delta w_j(n) = F(y(n), x_j(n)) \quad (2)$$

where $F(y(n), x_j(n))$ is a function of correlation between the neuron output $y(n)$ and j th input signal x_j . The key point for this process to work is that there must be *correlation* or *redundancy* in the input signals. In this case, the neural network tries to find the correlation of the input and use that for future data.

The beauty of SOM lies in its ability to achieve global order through performing local interactions between neurons and the environment. In order to do so, the synaptic weights adapt to locally-generated temporal signals. This attribute makes SOM a promising candidate for DSM in CR networks, building on the notion that the DSM problem is a time-variant and location-dependent optimization problem in which the CR units try to adapt to the temporal environment features, that is, spectrum configuration. Furthermore, SOM is based on the Hebbian learning rule, which is computationally simple.

B. SODSM

Our self-organizing DSM technique tries to extract the wireless set-up through a simple Hebbian learning rule. In this scheme, CR units communicate with their neighbouring CR units and share their radio scene analysis with them.

This information-sharing results in improved primary user detection [13]–[15] and also improves the learning process in SODSM. In order to perform this sharing, we assume that there is a feedback channel available between neighbouring CR units, thorough which they share their information and perform synchronization and control tasks. Thus, the formation of the CR network has two stages:

- 1) The CR units form a low bitrate ad-hoc network over an unlicensed band; this network is used to maintain synchronization and exchange control data.
- 2) When the CR units need to send data, they establish links using the available spectrum holes.

Clearly, the feedback channel cannot be established using spectrum holes in the licensed bands because they change fast and sometimes they may not be available at all. Therefore, the low-bandwidth feedback channel must be established in the unlicensed bands. In this work, we assume that this feedback channel is already established and available. For example, the feedback channel can be formed using one of the several available ad-hoc wireless network standards operating on unlicensed bands such as Bluetooth or adhoc 802.11 [16], [17]. Using such a feedback channel, the CR network is always operational and CR units never loose synchronization and control.

In the CR network environment, there are two types of changes happening by PUs:

- 1) Soft changes, which are starting or stopping operating on a spectrum band.
- 2) Hard changes, which are moving in or out of interference range of a CR unit.

Ideally, CR units can increase the spectrum utilization efficiency to 100 % by following soft changes and use any spectrum hole which is available and avoid it as soon as a PU starts using it. However, in practice such a policy would result in a high probability of collision with PUs because CRs monitor their surrounding environment through their radio scene analysis (RSA) unit and RSA unit has a *time delay* D_{RSA} in analyzing the radio scene. Therefore, if a CR uses a sub-band b_i that is free but there is an inactive PU present in its interference range which operates on b_i , each time the PU becomes active, a collision with duration D_{RSA} happens. Therefore, CRs must follow the hard changes in the environment and avoid using sub-bands that are free but have inactive PUs operating on them. Unfortunately, CR units can only observe soft changes and can not monitor the hard changes directly. In SODSM, CR units try to estimate the presence of PUs by looking at their recent past activities. There is a correlation between a PU's presence and its recent past activities. If there has not been any PU activity in a sub-band in recent past, it is likely that there is no PU using that sub-band present in the environment. On the other hand, if there have been

some activities in the recent past in a sub-band, it is likely that there is a PU operating on that sub-band present even though that sub-band is free at the moment.

The SODSM uses Hebbian learning rule to estimate the presence of PUs in the environment by using this correlation. In SODSM, CR units continuously monitor their surrounding environment and save the information they obtain in a vector termed *channel allocation priority list (CAPL)*. This vector's size is equal to the total sub-channels N_{ch} , and CR units keep a weight w_i for each sub-band b_i in it that represents how long b_i has been free in recent past and thus how likely it will be free in near future. This weight is continuously updated for each CR, C_m , using the following learning rule:

$$w_{i,m}(n+1) = \begin{cases} w_{i,m}(n) + \eta, & \text{if } b_i \text{ is free} \\ 0, & \text{otherwise.} \end{cases}$$

where $1 > \eta > 0$ is the learning rate, and $w_{i,m}(n+1)$ is maintained between 0 and 1 to use it as a probability measure. Using this rule, at each round the weights for available sub-bands increase by η and would become 1 if no PU uses them for at least $\lfloor \frac{1}{\eta} \rfloor$ consequent time steps where $\lfloor x \rfloor$ denotes the integer part of x . As soon as a PU is detected on b_i , w_i is set to zero and will not be used by the CR unit even if becomes free, until it has been free for sufficient time to allow w_i grow and reach a certain threshold τ . This simple rule can establish a self-organizing DSM among CR units, which only depend on the neighbouring CR units and local environmental configuration.

When CR units need to establish a communication link, they choose the *best* sub-band using these weights. The best sub-band b_j for two CR units C_i and C_k must satisfy three conditions:

- 1) b_j is free for both C_i and C_k ;
- 2) $w_j > \tau$ for both C_i and C_k ;
- 3) b_j maximizes $w_i(n, j)w_k(n, j)$ in accordance with $\arg(\max_j (w_i(n, j)w_k(n, j)))$

A larger τ means a more conservative policy and decreases the probability of collision with PUs because CR units need to wait longer before they consider a sub-band free. However, a more conservative policy also decreases the spectrum utilization of CR network.

IV. SOFTWARE TESTBED

In order to evaluate the emergent behaviour of CR network using the SODSM technique, we have developed an agent-based software testbed. This testbed is written in C++ and is currently deployed on the Sharnet [18]. It is capable of simulating a CR *adhoc* network along with legacy network and users, and measures the spectrum utilization efficiency over the scope of simulation.

In this software testbed, we assume that the spectrum band is divided into N_{ch} equal sub-bands. The legacy network has two types of radios: base station and mobile units. Similar to GSM systems, it is assumed that when mobile users are operating, one sub-band is used for uplink and another one for the downlink and both are occupied as long as the mobile user is active. The CR units have separate RX and TX modules; thus, they can receive data from a CR unit while sending data to another one. The traffic model used for both networks is a Markov model [19] in which each transmitter has two states of idle or transmitting (TX). At each time instance, if it is in the idle state, it may go to the TX state with probability p_1 and if it is in the TX state, it may go to the idle state with probability p_2 . The channel noise level is set to -100 dBm, maximum transmit power for transmitters is 50 dBm and the channel model used is of degree 4 as used in [20], [21]. The spectrum is monitored through a grid of probes. At each time instance, each probe counts the number of sub-bands occupied by radios that are in its interference range. The interference range is obtained by requiring at least 15 dB of signal to noise and interference ratio (SINR) for the received signal, as in [20], to be detectable. Define $S_{cr}(i, n)$ as the number of the sub-bands used by the CR network at time n and i th probe $Prob_i$. Similarly, $S_{leg}(i, n)$ is the number of the sub-bands occupied by the primary network; then, the spectrum utilization efficiency at $Prob_i$ is obtained from:

$$e_i(n) = \frac{S_{cr}(i, n) + S_{leg}(i, n)}{N_{ch}}$$

After running the simulation for T_{tot} time-steps, \hat{e}_i , the average spectrum utilization at $Prob_i$ and $\hat{e}_{network}$, average spectrum utilization over the whole simulated area are calculated respectively from:

$$\hat{e}_i = \frac{\sum_{n=1}^{T_{tot}} e_i(n)}{T_{tot}}, \quad \hat{e}_{network} = \frac{\sum_{i=1}^{N_{prob}} \hat{e}_i}{N_{prob}}$$

Another metric that the software testbed measures is P_{col} , *probability of collision*. Collision happens when a PU is operating on a sub-band and a CR unit in the interference range of the PU also operates on that band. For the i th PU, $P_{col,i}$ is defined as:

$$P_{col,i} = \frac{T_{col,i}}{T_{use,i}}$$

where $T_{col,i}$ is total collisions happened in i th PR and $T_{use,i}$ is the total time-sub-bands it has used during the simulation. Any CR network should ideally have it equal to zero; however in practice due to RSA delay D_{RSA} , P_{col} is always larger than zero. Thus, one of the objectives in the DSM design is to minimize this probability.

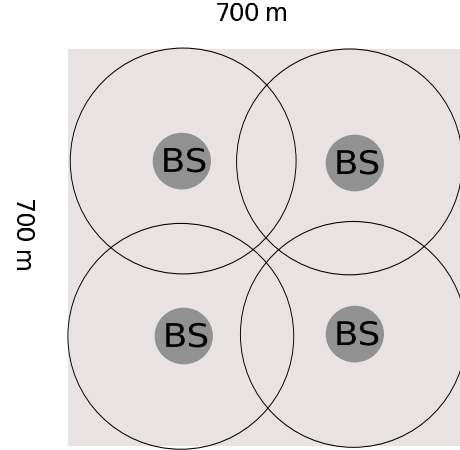


Figure 2. The simulated area with four base stations.

Finally define N_{intr} as the average number of interruptions during the CR communications due to PUs starting to use the same band. In order to have a more reliable communications in the CR network, we would like to have N_{intr} as small as possible, ideally zero.

A. Simulation results

To evaluate our DSM scheme, we have used the testbed to simulate a wireless network using two DSM schemes:

- 1) Self-organizing DSM
- 2) Random DSM (RDSM), in which sub-bands are chosen randomly from the available spectrum holes.

The simulated area, shown in Fig. 2, is a $700 \times 700 m^2$ square with four base stations covering approximately all the area. Among the total 30 sub-bands, 24 sub-bands are licensed for the primary network and each BS uses 3 for uplink and 3 for downlink. In each simulation, the total simulation time was 2×10^5 and each simulation was repeated at least 1500 times. In each round, $N_{cr} = 500$ CR units and $N_{PU} = 200$ PUs were randomly placed in the simulated area. The CR's radio scene analyzer was assumed to have PU detection delay $D_{sc} = 1$ sampling period. We have performed 3 simulations, first one using RDSM (S_1), second one using DSM with $\tau = 0.1$ (S_2) and the last one using a more conservative SODSM with $\tau = 0.3$ (S_3). Table I shows the DSM parameters for these three simulations.

The simulation results are illustrated in Fig. 4, 3 and 5. As shown in Fig. 3, the CR network spectrum utilization is approximately equal to 0.19 for S_1 and S_2 and is 0.10 for S_3 while primary network spectrum utilization is found to be 0.17 for all simulations. The probability of collision during PU TX, $P_{col,TX}$, is reduced from 1.3×10^{-4} for S_1 to 5×10^{-5} for S_2 and 3.2×10^{-6} for S_3 . Similarly, $P_{col,RX}$ is reduced from 1.9×10^{-4} for S_1

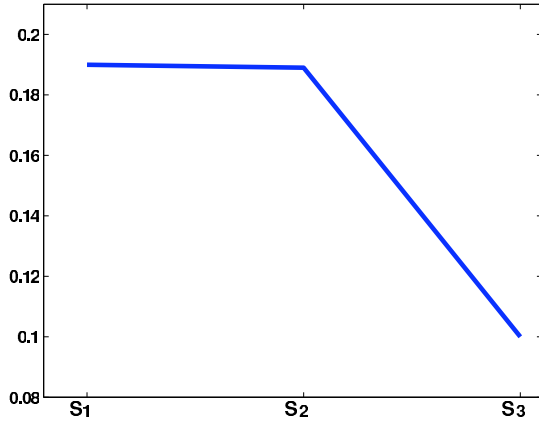


Figure 3. Spectrum utilization of CR network.

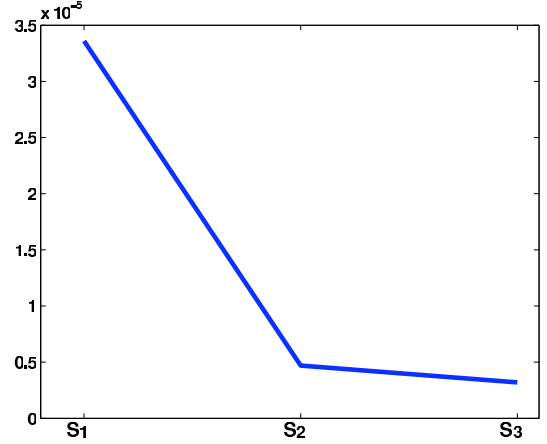


Figure 5. Average number of interruption for CR units.

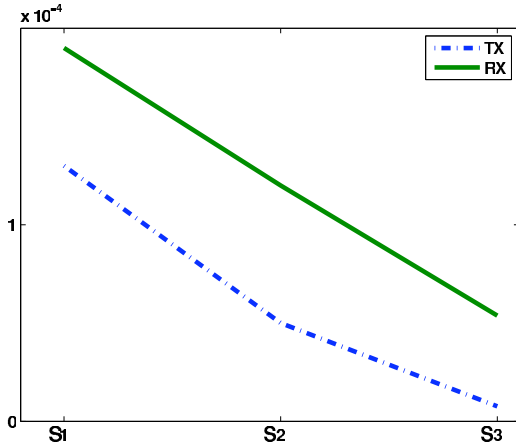


Figure 4. Probability of collision during TX and RX for legacy network.

to 1.2×10^{-4} for S_2 and 5.3×10^{-5} for S_3 . Clearly, we can see a significant decrease in the P_{col} using SODSM compared to RDSM. However, using the more conservative scheme S_3 , the CR network spectrum efficiency $\hat{\epsilon}_{network}$ is reduced from 0.19 to 0.10 which is the price paid for the much larger decrease in the P_{col} . Note that the decrease in $P_{col,RX}$ is not as large as $P_{col,TX}$ due to the fact that detecting receiving PUs is more challenging and sometimes they can not be detected using RSA methods. Finally,

Simulation	S_1	S_1	S_1
DSM	RDSM	SODSM	SODSM
η	-	0.01	0.01
τ	-	0.1	0.3

Table I
DSM PARAMETERS FOR THE THREE SIMULATIONS.

Fig. 5 shows the N_{intr} for these three simulations. As shown in this figure, N_{intr} is equal to 3.3×10^{-5} for S_1 , 4.7×10^{-6} for S_2 and it is reduced to 3.2×10^{-6} for S_3 . Clearly, SODSM has succeeded to reduce the number of interruptions and provide a more reliable communications for the CR network. The results show that using SODSM decreases the probability of collision significantly with a relatively small decrease in the CR network spectrum utilization.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have described a novel decentralized scheme for dynamic spectrum management (DSM) using principles of self-organization (SO), hence the acronym SODSM. The SODSM scheme tries to follow the hard changes in the environment and thereby assess the wireless configuration. Following the hard changes results in fewer collisions with PUs and also lower spectrum utilization. Using a computationally simple learning rule, namely Hebbian learning, it extracts the environmental configuration and adapts to it. As the configuration changes, the SODSM detects the changes and avoids using sub-bands that may be used by PUs.

In order to evaluate the SODSM scheme, a software testbed has been developed which can simulate a network of CR units along with one or several primary networks. This testbed measures various critical metrics of the emergent behaviour of a CR network such as spectrum utilization efficiency and probability of collision with primary users.

We performed the simulation using two SODSMs and also RDSM. The results show that the more conservative SODSM results in a significantly lower P_{col} and N_{intr}

compared to RDSM, while $\hat{e}_{network}$ is reduced to approximately half. The less conservative SDSM S_2 has resulted in equal spectrum efficiency and N_{intr} and still decreased P_{col} . Therefore, there is a trade off in SODSM between P_{col} and $\hat{e}_{network}$. By tuning τ , it is possible to decrease P_{col} (increase $\hat{e}_{network}$) with the price of a decrease in $\hat{e}_{network}$ (increase in P_{col}). However, these metrics can not be tuned to any arbitrary value and may change inside a boundary imposed by several parameters such as D_{RSA} , density of CR units, density of PUs, N_{ch} and traffic load parameters of PUs and CRs.

The goal of a CR network is to increase spectrum utilization efficiency and provide reliable communications at all times and locations while decreasing the collision with PU network to ideally zero or at a tolerable level. The SODSM is an attractive DSM scheme for CR networks since it is scalable and computationally simple, and can increase the spectrum efficiency while decreasing the collision with primary network. Current work centres on improving the learning rule and running extensive simulations on our testbed to evaluate overall performance on different network conditions.

To conclude, as complexity is increasingly growing in technology and its applications, self-organization has gained a lot of attention for solving challenging problems. In particular, a self-organized wireless network offers several advantages: ease of installation, high reliability and low cost. In this context, cognitive radios – a new frontier in wireless communications – are required to provide reliable communications whenever and wherever needed. With these attributes in mind, CRs should be self-organized so as to operate in infrastructure-free environments as described in this paper. Furthermore, we have shown that while self-organized DSM is computationally simple, it can result in high spectrum utilization and low interference on primary networks. We are therefore emboldened to say that self-organized CR networks have the potential for becoming a disruptive technology.

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