Spectrum resource optimization for future cellular networks

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Abstract. During the last few years cellular networks have increased the use of spectrum resources due to the success of mobile broadband services. Making new exclusive spectrum available to meet traffic demand is challenging since spectrum resources are finite therefore costly. Cognitive radio (CR) technology along with spectrum sharing strategies is proposed as a solution that can reuse the limited spectrum resource. In order to meet mobile traffic demand is expected that future cellular networks overlaid femto-cells (small cells) on the existing macrocell network. To extend and share a common spectrum, femto-base station (femto-BS) is empowered with CR technology. In this paper, we present evaluation of a cognitive cellular network using a spectrum resource strategy based on binary particle swarm optimization (BPSO).

Keywords: cognitive radio, spectrum sharing, binary particle swarm optimization

1 Introduction

The continued growth and demand satisfaction of future cellular networks depends on the availability of spectrum resource. Currently, spectrum resource is underutilized due to Static Spectrum Allocation Policy as some studies pointed out [1] underling the need for a more flexible and efficient spectrum management. In this context, spectrum sharing techniques are proposed as a solution to reuse available spectrum through Cognitive Radio (CR) technology. It will enable the coexistence of primary (user with higher priority to access the spectrum) and secondary (users with lower priority to access to spectrum) radio nodes on the same spectrum band to improve the spectral efficiency. In order to access to a channel, a secondary user could perform one of the following spectrum sharing strategies: transmit simultaneously with the primary user as long as the resulting interference is constrained (spectrum underlay), or exploit an unused channel of primary user (spectrum overlay) [2].

In order to meet mobile traffic demand is expected that future cellular networks overlaid femto-cells (small cells) on the existing macrocell network. To extend and share a common spectrum, femto-base station (femto-BS) is empowered with CR technology. A femto-BS with CR technology is able to adapt optimally their operating parameters according to interactions with the surrounding radio environment [3]. Either if a femto-BS performs overlay o underlay spectrum sharing strategies an admission and interference control approach should be taken into consideration to assure protection to primary user, that is, to guarantee that its communication cannot be disrupted due to share the channel. However, certain Quality of service (QoS) should also be taken into account in the secondary user side to provide significant benefits to both primary user and secondary user from spectrum sharing. Therefore, it is necessary to quantify the effect of the femtocells networks (secondary users) interference on the macrocell network (primary user) performance. A potential application of femtocells is envisioned when a large number of users congregate at the same time such as in case of game stadiums. Under this situation, the macrocell network is likely to be overloaded due to the large amount of data generated. If some of this data can be offloaded to additional spectrum, such as femtocells, the users can be served [4].

In this paper we show performance system in terms of number of admitted secondary links coexisting with primary links, and maximum throughput. We consider throughput as a metric of spectral efficiency and spectrum underlay as the spectrum sharing technique. We focus on the downlink analysis since it is more critical in terms of femto-macro interference [5]. The solution procedure is based on an improved version of Binary Particle Swarm Optimization (BPSO) algorithm [6], known as Socio-Cognitive Particle Swarm Optimization (SCPSO) [7].

In some works performance results about admission and interference control in cognitive cellular networks are presented. In [8] is evaluated the performance of different sharing schemes (interweave, underlay, controlled underlay) in terms of transmission capacity. Numerical results conclude that controlled underlay scheme provides improved spatial reuse. On the other hand, in [9] an adaptive resource management strategy based on game-theory is proposed. It employs power control to mitigate interference among femtocells and macrocell. It concludes that when femto-BSs recognize the interference sources, interference management in cellular networks is enhanced therefore a higher throughput is achieved for femtocells. Its main drawback is that it only considers maximizing throughput of femtocells, furthermore, its shutdown process in femto-BSs can introduce additional computational time. The downlink spectrum sharing on overlay mode is addressed in [10] to improve network capacity, and mixed primal and dual decomposition methods are applied to solve it. However the time complexity is an issue. Another downlink spectrum sharing on overlay mode is presented in [11], a game theory is used to mitigate cross-tier and intra-tier interference, the spectral efficiency is in terms of the concept of effective capacity which is defined as the maximum constant arrival rate that can be supported by the system while satisfying the given QoS requirement. Channel sensing introduces an overhead since data transmission and reception cannot be performed within a sensing frame. In [12] an admission control algorithm to manage interference in two-tier femtocell network is proposed and QoS is provided for macro-cell and femto-cells. However, when the network becomes congested, the admission control algorithm converges slowly down. It also presents unfairness since higher QoS for macro-users can be improved at the cost of degrading the QoS of the femto-users.

The remainder of this paper is organized as follows: In section 2, we present the system model and we introduce the solution procedure based on SCPSO. Section 3 shows simulation results. Section 4 concludes this paper.

2 Macro-Femto spectrum sharing approach

The macrocell consists of multiple macro-users and a macro-Base Station (macro-BS) located at the center of a coverage area *A*, then a number of femtocells are randomly distributed on *A*. A secondary link is represented by the union of a transmitter (femto-BS) and a receiver (femto-user) and it is identified by a number beside the link. Similarly, the union of a transmitter (macro-BS) and a receiver (macro-user) is referred as a primary link. A primary link has a primary channel to share (the numbers in braces in Fig. 1) and it can be assigned to several secondary links (the number in brackets in Fig. 1), as long as they, together, do not disrupt communication in the primary link. *Pl* and *Sl* represent the set of primary and secondary links respectively. To assure successful communications for those secondary links that attempt to exploit concurrently a channel with a primary link, a certain QoS is also guaranteed for them (denoted by α). Macro-BS and femto-BSs transmit at any given channel at full power; therefore, transmission power is maintained constant.

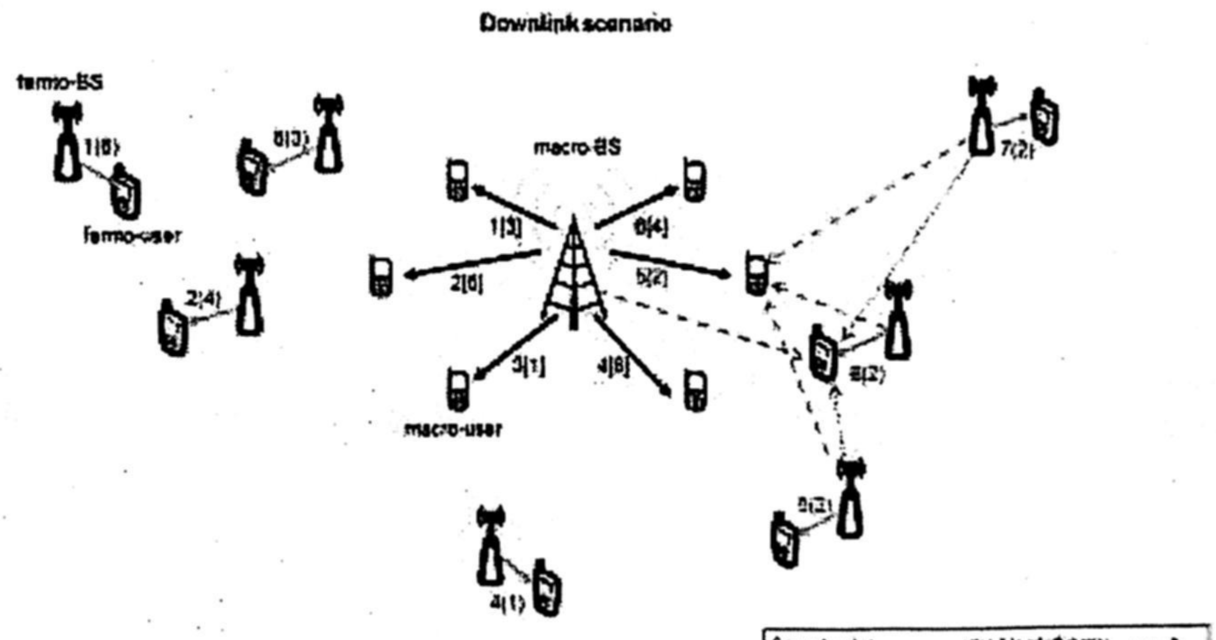

Fig. 1. Downlink interference scenario in macro-femtocellular networks

A successful reception of a transmission at a primary link depends on whether the signal-to-interference-plus-noise ratio (SINR) observed by macro-user is larger than an SINR threshold (denoted by β). The SINR at the receiver of primary link v is given by:

$$SINR_v = \frac{P_v / ldp(v)^n}{\sum_{k \in \Phi} P_k / dps(k,v)^n}, \; 1 \leq v \leq Pl \qquad (1)$$

where P_v is the transmit power of primary link v, $ldp(v)$ is the link distance of primary link v, n is the path loss exponent (a value between 2 and 4). Those parameters characterized the desired signal. On the other hand P_k is the transmit power of secondary link k, $dps(k,v)$ is the distance from transmitter in secondary link k to receiver in primary link v. k is the index of active secondary transmitters. Φ is the set of active secondary transmitters. The aforementioned refers to the aggregated cross-tier interference, that is, the total interference from those secondary links using the same channel that primary link being analyzed as show in Fig. 1 in which $SINR_v$ is computed in primary link 5.

In contrast, the SINR at the receiver of secondary link u is given by:

$$SINR_u = \frac{P_u / lds(u)^n}{\sum_{k \in \Phi} P_k / dss(k,u)^n + P_v / dps(v,u)^n}, \; 1 \leq u \leq Sl \qquad (2)$$

where P_u is the transmit power of secondary link u and $lds(u)$ is the link distance of secondary link u. Meanwhile, P_k is the transmit power of transmitter of secondary link k, $dss(k,u)$ is the distance from transmitter of secondary link k to receiver of secondary link u. The above represents the aggregate intra-tier interference. In contrast, P_v is the transmit power of primary link v, $dps(v,u)$ is the distance from transmitter of primary link v to receiver of secondary link u. That refers the cross-tier interference perceived by a receiver of secondary link u. α represents SINR threshold for secondary links. Fig. 1 shows $SINR_u$ computed in secondary link 6.

Data rate contributions of the secondary and primary links are derived from equations (3) and (4) respectively. The data rate depends on channel bandwidth B that secondary and primary links can share and the conditions of the propagation environment (attenuation and interference).

$$c'_u = B \log_2 (1 + SINR_u) \qquad (3)$$

$$c''_v = B \log_2 (1 + SINR_v) \qquad (4)$$

The metric considered as a measure of spectral efficiency on the cognitive cellular network is data rate, therefore the objective of resource allocation is to find the maximum data rate of system (5) subject to the SINR requirements of the secondary links (6) and primary links (7), that is:

$$Max \sum_{u=1}^{Sl} c'_u x_u + \sum_{v=1}^{Pl} c''_v \qquad (5)$$

$$SINR_u \geq \alpha \qquad (6)$$

$$SINR_v \geq \beta \qquad (7)$$

$$c'_u > 0, \; u=1, 2, \ldots, Sl \qquad (8)$$

$$c''_v > 0, \; v=1, 2, \ldots, Pl \qquad (9)$$

$$c'_u, \; c''_v \in R^+ \qquad (10)$$

$$x_u = \qquad (11) \begin{cases} 1, \text{ if } SINR_u \geq \alpha \text{ and } SINR_v \geq \beta \end{cases}$$

0, otherwise

where $x_u = 1$ if secondary link u is included in the solution and $x_u = 0$ if it remains out as indicated in (11).

To find the set of secondary links that can maximize the data rate of cognitive cellular network without degrading the QoS of both the macrocell and the femtocells, a systematic procedure based on BPSO is used, in particular, the SCPSO. In BPSO methods, a swarm is composed as a number of particles S and a particle (vector X_i) represents a candidate solution of the problem. Each particle X_i has its own velocity (vector V_i) and memory (vector P_i) in which the best solution found by the particle so far is recorded (*pbest*). On the other hand, the best solution found by the whole swarm is called *gbest (vector* P_g*)*. At each iteration, the particle evolves taking into account the best solution found in its path, *pbest*, and the leader, *gbest*, until a stop condition is met. The algorithm to address the spectrum sharing problem in the cognitive cellular network is as follows:

Input: The number of secondary links *Sl*, the number of primary links *Pl*, SINR thresholds $\alpha=\beta$, the number of particles *S*, and the number of iterations and T_{max}, the number of runs.

Output: Maximum data rate in the system $f(P_g)$, the set of selected secondary links P_g, channel allocation for primary links *vector Spectrum Status*, the best channel allocation for secondary links P'_g, SINR level at primary links, and SINR level at secondary links.

Step 1: It is the initialization stage, it includes:

1.1: Locate randomly *Sl* and *Pl* over the coverage area *A*

1.2: Initialize randomly candidate solution vector X_i, where $x_{id} \in \{0,1\}$

1.3: Initialize randomly velocity vector V_i, where $v_{id} \in [-V_{max}, V_{max}]$

1.4: Set $P_i = X_i$

1.5: Let coincide the personal best channel allocation vector P'_i and candidate channel allocation vector X'_i

1.6: Initialize randomly vector *Spectrum Status* with values from *Pl*.

Step 2: The update P_i stage. Particle compares $f(X_i) > f(P_i)$ according to objective function in equation (5) and restrictions in (6)-(11), and overwrites P_i if $f(X_i)$ is higher than $f(P_i)$.

Step 3: The update P_g stage. P_i values will be compared with current P_g value, so if there is a P_i which is higher than current P_g, it will be overwritten.

Step 4: Update elements in X_i and V_i according to the following equations:

$$v_{id} = w \times v_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \quad (12)$$

$$v_{id} = w^1 \times v_{id} + c_3\,(gbest - pbest) \quad (13)$$

$$x_{id} = x_{id} + v_{id} \quad (14)$$

$$x_{id} = x_{id} \bmod (2) \quad (15)$$

where c_1 and c_2 are the learning factors, c_3 is the socio-cognitive scaling parameter, r_1 and r_2 are random numbers uniformly distributed in [0,1], w and w^1 are the inertia weights.

Step 5: If $x_{id} = 1$ then allocate randomly a new channel to x'_{id} from the set of primary links *Pl*.

Step 6: For each particle in the swarm, perform Step 2 – Step 5

Step 7: Repeat Step 2- Step 6 until stopping criterion met.

3 Performance evaluations

We deploy the downlink of a CDMA (Code Division Multiple Access) in two-tier heterogeneous network following the model described in section 2 and shown in Fig. 1. A number of secondary links *Sl* are randomly spread over an area of 5000 m x 5000 m (macrocell range). Also, there are six primary links, *Pl*, which have fixed locations. Each secondary transmitter (femto-BS) is assumed to have an assigned receiver at a random limited distance (30 m), *r*, away. Moreover, each transmitter is assumed to employ unit transmission power and the channel strength to be determined by path loss. We treat interference as noise, assume that the ambient/thermal noise is negligible, and assert transmission success to be determined by the SINR lying above a specific threshold where $\alpha=\beta$.

The snapshot of the location of *Pl* and *Sl* present in the area is called a scenario. An experiment is defined by a set of scenarios (with same *Sl* and *Pl*) at given SINR threshold. By imposing different SINR thresholds, we simulate different requirements for mobile applications to guarantee a good service. At each experiment, 500 independent runs are taken. Each run represents a different placement of the *Sl* in a scenario. The stopping criterion for a run is defined by the maximum number of iterations T_{max}. The simulation parameters are given in Table 1.

Table 1. Simulation parameters

Parameters	Value
Number of secondary links *Sl*=	20
Number of primary links *Pl*=	6
Channels to share =	1, 2, 3, 4, 5, 6
Runs =	500
SINR thresholds $\alpha=\beta$	4, 6, 8, 10, 12, 14 dB
Channel bandwidth =	20 MHz
Swarm size S =	40
Maximum number of iterations T_{max}=	100
Cognitive, social and socio-cognitive factors c_1, c_2, c_3 =	2, 2, 12
Inertia weight w=	0.721
Maximum velocity V_{max}=	[-6,6]

From the set of 500 runs that are evaluated for a given experiment at a SINR threshold ($\alpha=\beta$), the run containing the maximum data rate of the system is taken and that information is analized and reported in Table 2. Those results suggest that the higher the SINR threshold, the data rate decreases since the requested QoS is higher and it restricts the number of admitted secondary links coexisting with the primary links. This last observation is consistent with results reported in [13] which concludes that increasing the SINR threshold decreases the permissible number of secondary links. Also from Table 2, it is shown that for higher SINR thresholds is more challenging to share a channel, in this case, from SINR values at 10 dB. Then the network capacity directly depends on the interference limit established in the cognitive cellular network.

Table 2. The best found at each experiment

α=β (dB)	Maximum system throughput (Mbps)	Number of selected secondary links allocated to primary channels						Total number of selected secondary links
		Ch 1	*Ch 2*	*Ch 3*	*Ch 4*	*Ch 5*	*Ch 6*	
4	9828.3486	4	2	2	2	2	4	16
6	9376.8802	2	5	1	3	2	3	16
8	9585.0736	1	2	3	4	5	2	17
10	8877.6855	3	3	3	5	2	0	16
12	9295.4222	0	2	5	2	2	5	16
14	8648.4162	4	2	1	3	3	2	15

Reusing spectrum bands represents benefits in terms of spectral efficiency as long as band-specific conditions are imposed to those which are allowed to access the same range of frequencies. If not conditions are imposed, it can lead to a "tragedy of the commons" in which many users try to access the same spectral resource and neither is able to communicate reliably given the amount of interference. Those conditions are regulatory policies which represent specifications of network deployment and operation to avoid harmful interference among coexisting systems. Some examples of specifications of network deployment are number of selected secondary users, exclusion zones (radius of protection of a primary user), transmission power, and SINR thresholds.

4 Conclusion

In two-tier heterogeneous network, we study the spectrum resource optimization problem. We aim at maximize the throughput of the system as a metric of spectral efficiency under QoS constraints. Then an adaptive resource management framework based on an improved version of binary particle swarm optimization is applied to solve the problem.

The numerical results have shown that, network performance depends directly on the value of requested QoS in the system i.e., taking into consideration the requirements of primary and secondary users. They also suggest that is possible that a set of secondary users can share simultaneously with the primary user a channel, as long as, certain conditions are imposed to secondary users.

Regulation is a key role to support spectrum sharing, in this context, identify design requirements for deploying future cellular networks based on CR technology is helpful for developing regulatory policies that assure a peaceful coexistence among heterogeneous systems.

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