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Primary user localisation and uplink resource allocation in orthogonal frequency division multiple access cognitive radio systems

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Abstract: In cognitive radio networks, secondary users (SUs) can share spectrum with primary users (PUs) under the condition that no interference is caused to the PUs. To evaluate the interference imposed to the PUs, the cognitive systems discussed in the literature usually assume that the channel state information (CSI) of the link from a secondary transmitter to a primary receiver (interference link) is known at the secondary transmitter. However, this assumption may often be impractical in cognitive radio systems, since the PUs need to be oblivious to the presence of the SUs. The authors first discuss PU localisation and then introduce an uplink resource allocation algorithm for orthogonal frequency division multiple access-based cognitive radio systems, where relative location information between primary and SUs is used instead of CSI of the interference link to estimate the interference. Numerical and simulation results show that it is indeed effective to use location information as a part of resource allocation and thus a near-optimal capacity is achieved.

1 Introduction

Cognitive radio (CR) systems have received a great deal of attention recently as future radios. CR systems allow the intelligent users to share the spectrum with the existing systems without causing interference [1, 2]. To perform this task, CR systems require the capability of sensing the spectrum to search the frequency bands that are not currently being used, called spectrum holes, and flexibility to avoid occupied frequency bands and using those available frequency bands selectively. Since orthogonal frequency division multiple access (OFDMA), which is widely used in various wireless multiuser systems, offers high spectral efficiency and flexibility of using partial frequency band, OFDMA is attractive for CR systems.

To maximise the capacity of OFDMA systems by exploiting time-varying nature of fading channels and independent channel statistics among multiple users, resource allocation problems have been one of the most active research topics. An extensive research has been recently performed for resource allocation in CR networks [3–14]. Many of them assume that the instantaneous channel gain or the channel state information (CSI) of the interference links from secondary transmitters to primary receivers is available. However, since primary users (PUs) are oblivious to secondary users (SUs), CSI estimation of the interference links at the primary receivers is generally not possible. Furthermore, it is impractical in CR systems to assume that PUs send feedbacks to SUs. Without the CSI of the interference links, secondary transmitters cannot estimate the potential interference at PUs. Therefore, it is not possible to share the frequency bands used by the PUs but may have to avoid transmission over those frequency bands. In [15], the authors investigated downlink and uplink resource allocation problems in CR systems based on the knowledge of distances between a PU and SU. It is assumed in [15] that the locations of the PUs and the SUs are known a priori. Since it is a strong assumption, therefore in this paper a more practical scenario is considered where the location of a PU is not known a priori.

If the interference at the PUs can be estimated, then the SUs can use some interference-free transmit power and share the frequency bands that are being occupied by the PUs, which allows a more efficient use of the spectrum. As such, it is of paramount importance to estimate the interference caused to the PUs under the condition of no CSI of the interference links and further perform resource allocation to maximise the system capacity of the secondary network. In [16], the authors propose a power allocation algorithm that requires the statistics and not instantaneous CSI of the interference link in OFDM-based CR systems, whereas [17] considers a scenario where only some PUs CSI is available at the secondary transmitter and proposes a resource allocation algorithm based on rate loss constraint. In [18], the authors propose a power allocation algorithm based on the mean value of the channel gain for the given interference link.

Location awareness [19] has realised huge advancements in cellular networks during the last decade owing to the emergence of more accurate and faster algorithms for cooperation techniques [20–22]. Together with the wireless technology expansion, new and interesting problems are arising for localisation. The typical examples are ‘Internet of things’ (IoT) and e-health with wireless body area networks (WBAN) IEEE 802.15.6. Some other common application scenarios of localisation includes industrial, medical, household, marine, military and environment monitoring. In CRs, the availability of location information (LI) allows an opportunity for system optimisation in various aspects such as:

- performing more precise measurements of the spectrum occupancy;
- determining the minimum transmit power level for a reliable link between SUs;
- determining angle of arrival/departure towards PUs and using beamforming technique to reduce the interference to the PUs if multiple antennas are available;
- optimising the CR networks to maximise the spatial reuse;
- constructing the optimal secondary network topology based on the given primary networks;
- performing more accurate spectrum sensing by adjusting the detection threshold that enables a precise interference control within resource allocation algorithms.

Motivated by these observations, we show in this paper that LI is very useful in estimating the interference power at the PUs even without CSI, which allows an efficient and practical spectrum-sharing scheme for CR systems. Unlike CSI, the location of a PU is possible to obtain by user cooperation in CR systems. One of the great benefits from the knowledge of PU's LI is the estimated distance between PU and SU and the estimated transmit power from the PU to the SUs. The estimated distance and the transmit power level of the PU are important parameters, since those can be used to evaluate the amount of interference to the PU, which helps achieve a higher resource allocation performance.

The main contribution of this paper is two-folded and is summarised as follows: First, weighted least square (WLS) algorithm for localisation of a PU is proposed. This proposed algorithm only requires long-term average energy measurement from each cooperating SU. Since this measurement is already available in each SU while spectrum sensing is performed, little extra effort is needed for the proposed algorithm. Secondly, to evaluate the usefulness of the proposed localisation algorithm, an uplink resource allocation algorithm is discussed with the goal of maximising the total capacity of the OFDMA-based SUs based on the LI of the PU under the condition of statistical violation of the interference constraint. With the knowledge of the PU location, cooperative spectrum sensing may detect the PUs with a higher accuracy. This in turn results in lower probabilities of false alarm and miss detection.

2 System model

Consider a cellular CR network that consists of a secondary base station (single cell environment), K SUs and a PU who occupies some subchannels, where subchannel is defined as a group of subcarriers, in the spectrum, as illustrated in Fig. 1. The SUs aim to opportunistically use parts of the spectrum without causing a harmful interference to the PU. It is assumed that the PU operates in frequency division duplex mode, where different frequency bands are used for transmission and reception. The CRs use OFDMA with L subchannels and a wider system bandwidth than that of the PU in order to take advantage of the interference mitigation based on frequency diversity and the capability of a selective use of unoccupied subchannels by the PU. Interference temperature is defined as the radio frequency power measured at a receiving antenna per unit bandwidth and indicates the tolerable interference level at the PU [23].

In cooperative spectrum sensing algorithms, each SU takes energy measurements for a given frequency band for a certain period of time (not a long term) and reports these energy measurements from time to time to the fusion centre, which in turn makes a global decision whether a PU is present or not based on those measurements from the users. In addition to this regular measurement task, it is assumed that each SU also measures long-term average energy, which is denoted by R_k for the kth SU, for the purpose of PU localisation. We also assume that LI of the SUs is available at the secondary base station.

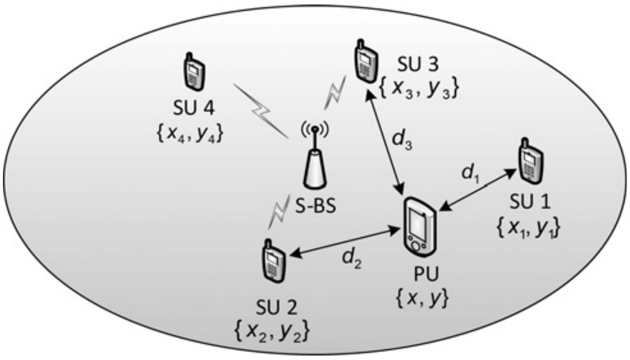

Fig. 1 *Cellular CR networks with a secondary base station, four SUs and a PU*

3 PU localisation

3.1 Estimation of the location of PU

Consider a CR network with a single PU and K SUs. The position of PU (target) is denoted by $\boldsymbol{x}_{\rm p} = \{x_{\rm p}, y_{\rm p}\}$, and the position of ith SU is $\boldsymbol{x}_{si} = \{x_{si}, y_{si}\}$. It is assumed that the locations of the SUs are known a priori. The Euclidean distance between a PU and ith SU is defined as

$$d_i = \| \boldsymbol{x}_{\rm p} - \boldsymbol{x}_{si} \| , \quad i = 1, 2, 3, \ldots, K \tag{1}$$

where $|\cdot|$ is the Euclidean norm. Generally, PUs are not cooperative in nature, thus distance between PU and SU cannot be calculated by a conventional method. For realistic CR network applications, the sensing information that is based on summed-energy (i.e. RSS) is adopted in the analysis [24, 25]. Each SU employs an energy detector which accumulates energy of n samples [26]. The accumulated energy denoted by ξ is compared to pre-determined threshold value of γ as follows

$$\xi = \sum_{k=1}^{n} y^2(k) \underset{H_0}{\overset{H_1}{\gtrless}} \gamma \tag{2}$$

where H_0 and H_1 corresponds to two hypothesis, respectively, that is, the absence and presence of PU signal $y(k)$. If the energy detected by the SU is greater than the threshold value γ, the PU is regarded as present. Once the PU is detected, then the received power at the ith SU is represented by

$$P_{r_i} = \gamma_i \left(\frac{P_{\rm t_p}}{\| \boldsymbol{x}_{\rm p} - \boldsymbol{x}_{si} \|^{\beta}} \right) \tag{3}$$

where γ_i is constant, $P_{\rm t_p}$ is the PU transmit power and β is the pathloss exponent. It is assumed that β is known a priori, which is possible by cooperation among SUs. Multiplying both sides of (3) by $2/\beta$, we obtain

$$\left(\frac{\gamma_i}{P_{r_i}} \right)^{2/\beta} = \frac{(x_{\rm p} - x_{si})^2 + (y_{\rm p} - y_{si})^2}{(P_{\rm t_p})^{2/\beta}} \tag{4}$$

which is expanded and written in matrix form as

$$\begin{bmatrix} 2x_1 & 2y_1 & \left(\dfrac{\gamma_1}{P_{r_1}} \right)^{2/\beta} & -1 \\ \vdots & \vdots & \vdots & \vdots \\ 2x_K & 2y_K & \left(\dfrac{\gamma_K}{P_{r_K}} \right)^{2/\beta} & -1 \end{bmatrix} \begin{bmatrix} x_{\rm p} \\ y_{\rm p} \\ (P_{\rm t_p})^{2/\beta} \\ \left(x_{\rm p}^2 + y_{\rm p}^2 \right) \end{bmatrix} = \begin{bmatrix} (x_1^2 + y_1^2) \\ \vdots \\ (x_K^2 + y_K^2) \end{bmatrix} \tag{5}$$

For the given value of pathloss exponent β, (5) is solved by linear least square method as

$$\boldsymbol{\Psi\Theta} = \boldsymbol{\Phi} \tag{6}$$

where

$$\boldsymbol{\Psi} = \begin{bmatrix} 2x_1 & 2y_1 & \left(\dfrac{\gamma_1}{P_{r_1}}\right)^{2/\beta} & -1 \\ \vdots & \vdots & \vdots & \vdots \\ 2x_K & 2y_K & \left(\dfrac{\gamma_K}{P_{r_K}}\right)^{2/\beta} & -1 \end{bmatrix} \tag{7}$$

$$\boldsymbol{\Theta} = \begin{bmatrix} x_{\mathrm{p}} \\ y_{\mathrm{p}} \\ (P_{\mathrm{t_p}})^{2/\beta} \\ \left(x_{\mathrm{p}}^2 + y_{\mathrm{p}}^2\right) \end{bmatrix} \tag{8}$$

and

$$\boldsymbol{\Phi} = \begin{bmatrix} \left(x_1^2 + y_1^2\right) \\ \vdots \\ \left(x_K^2 + y_K^2\right) \end{bmatrix} \tag{9}$$

The least square cost function based on (6), denoted by $C(\boldsymbol{\Theta})$, is

$$C(\boldsymbol{\Theta}) = (\boldsymbol{\Psi\Theta} - \boldsymbol{\Phi})^{\mathrm{T}}(\boldsymbol{\Psi\Theta} - \boldsymbol{\Phi}) \tag{10}$$

which is a quadratic function of $\boldsymbol{\Theta}$, indicating that there is unique minimum in $C(\boldsymbol{\Theta})$. The least square estimate corresponds to

$$\hat{\boldsymbol{\Theta}} = \arg\min_{\boldsymbol{\Theta}} C(\boldsymbol{\Theta}) \tag{11}$$

which is computed by differentiating (11) with respect to $\boldsymbol{\Theta}$

$$\hat{\boldsymbol{\Theta}} = \left(\boldsymbol{\Psi}^{\mathrm{T}}\boldsymbol{\Psi}\right)^{-1}\boldsymbol{\Psi}^{\mathrm{T}}\boldsymbol{\Phi} \tag{12}$$

The least square position estimates $\{\hat{x}_{\mathrm{p}}, \hat{y}_{\mathrm{p}}\}$ and transmit power is simply extracted from the first three entries of $\hat{\boldsymbol{\Theta}}$. Although the least square approach is simple, it provides optimum performance only when the noise is independent and identically distributed. The localisation accuracy is improved, if a symmetric weighting matrix $\boldsymbol{W}$ is included to cost function in (11). The resultant weighted least square cost function has the form of

$$C_{\mathrm{wls}}(\boldsymbol{\Theta}) = (\boldsymbol{\Psi\Theta} - \boldsymbol{\Phi})^{\mathrm{T}}\boldsymbol{W}(\boldsymbol{\Psi\Theta} - \boldsymbol{\Phi}) \tag{13}$$

where the weighting matrix $\boldsymbol{W}$ is given as

$$\boldsymbol{W} = \mathrm{diag}\left(\frac{\exp^{4P_{r1}/\beta}}{1 - \exp^{4P_{r1}/\beta^2}}, \frac{\exp^{4P_{r2}/\beta}}{1 - \exp^{4P_{r2}/\beta^2}}, \ldots, \frac{\exp^{4P_{rK}/\beta}}{1 - \exp^{4P_{rK}/\beta^2}}\right) \tag{14}$$

It can be seen from (13) that, given the location of the SUs, the unknown location and transmit power of PU is estimated. Once the location of PU is estimated, the fusion centre can estimate the distance between PU and SU and this estimated distance is used by SUs to avoid interference to the PU.

3.2 Estimation of interference to PU

Considering Rayleigh fading channel between the kth secondary transmitter and the primary receiver, the interference constraint at the primary receiver is only satisfied in a probabilistic (or statistical) manner because of fading effect. Thus, to limit a harmful interference at the primary receiver, we need to introduce the probability of maximum allowable violation of the interference constraint (the probability that the interference power at the primary receiver is higher than the interference). Thus, we formulate the following

$$\Pr[P_{\mathrm{rx}}(d_k) > \mathcal{I}^{\mathrm{th}}] \le p_\epsilon \tag{15}$$

where $P_{\mathrm{rx}}(d_k)$ is the instantaneous received power at the PU, $\mathcal{I}^{\mathrm{th}}$ is the maximum interference level tolerable by the primary receiver, and p_ε is the probability of maximum allowable violation of the interference constraint and is also called as interference outage probability [27]. Since $P_{\mathrm{rx}}(d_k)$ is distributed according to Rayleigh fading channel, (15) is re-written as

$$\Pr[P_{\mathrm{rx}}(d_k) > \mathcal{I}^{\mathrm{th}}] = 1 - \left(1 - \exp\left[-\frac{\mathcal{I}^{\mathrm{th}}}{\bar{P}_{\mathrm{rx}}(d_k)}\right]\right) \le p_\epsilon \tag{16}$$

Based on the location of the PU and SU, the distance between them is calculated by (1). When the kth SU transmits a certain power, the long-term average received power at the primary receiver can be computed by pathloss expression as

$$\bar{P}_{\mathrm{rx}}(d_k) = \frac{p_{k,i}}{d_k^\eta} \tag{17}$$

where $p_{k,i}$ denotes the transmitted power from the kth secondary transmitter on the ith subchannel, d_k is the distance between the kth SU and the PU, and η is the pathloss exponent. Substituting (17) into (16), we obtain

$$\exp\left[-\frac{d_k^\eta \mathcal{I}_{\mathrm{th}}}{p_{k,i}}\right] \le p_\epsilon \tag{18}$$

Given that $\mathcal{I}^{\mathrm{th}}$ is a constant, a lower p_ε results in a more conservative way of protecting the PU.

Using (18), we can further obtain the kth secondary transmitter's maximum transmit power that satisfies the interference constraint with the interference outage probability of p_ε when Rayleigh fading channel is present. Thus, the interference constraint with the interference outage probability of p_ε at the primary receiver for the ith subchannel is modelled by

$$a_{k,i} b_i \frac{p_{k,i}}{d_k^\eta} \le -\frac{\mathcal{I}^{\mathrm{th}}}{\ln(p_\epsilon)} \tag{19}$$

where $\ln(x)$ is the natural logarithm evaluated at x, $a_{k,i} = 1$ if the ith subchannel is allocated to the kth SU, otherwise $a_{k,i} = 0$, and $b_i = 1$ if the ith subchannel is occupied by the PU, otherwise $b_i = 0$, where b_i is assumed to be known by spectrum sensing [20].

4 Uplink resource allocation for OFDMA CR systems

4.1 Problem formulation

Using the estimation of interference, thanks to the knowledge of the location of PU, an uplink resource allocation algorithm is proposed to allocate the subchannels to the SUs in order to maximise the sum rate under the following constraints:

- No inter-SU interference: each subchannel is allocated to the maximum one user.
- Individual power constraint: each user has a limited power budget and the users cannot share their power.
- Interference constraint: SUs can share the subchannels occupied by the PU as long as the interference outage probability is less than p_ε.

This goal along with the constraints is formulated as

$$\max_{a_{k,i},p_{k,i}} \sum_{k=1}^{K}\sum_{i=1}^{L} a_{k,i}\log_2\left(1+\frac{|h_{k,i}|^2 p_{k,i}}{N_0}\right) \tag{20}$$

subject to

$$\sum_{k=1}^{K} a_{k,i} \le 1, \quad 1 \le i \le L \tag{21a}$$

$$\sum_{i=1}^{L} a_{k,i}p_{k,i} \le P_k, \quad 1 \le k \le K \tag{21b}$$

$$\sum_{k=1}^{K} a_{k,i}b_i\frac{p_{k,i}}{d_k^{\eta}} \le -\frac{\mathcal{I}^{\text{th}}}{\ln(p_\varepsilon)}, \quad 1 \le i \le L \tag{21c}$$

where P_k is the transmit power budget for the kth secondary transmitter, N_0 is the single-side noise power spectral density and $h_{k,i}$ denotes the channel coefficient between the kth secondary transmitter and the secondary receiver on the ith subchannel. Owing to this per-user power constraint in (21b), the optimal solution is far more challenging to obtain than the case with total power constraint such as downlink, since decoupling subchannel and power allocations do not provide the maximum capacity in uplink.

Using the method of Lagrange multipliers, we obtain

$$\begin{aligned}\mathcal{L} = &\sum_{k=1}^{K}\sum_{i=1}^{L} a_{k,i}\log_2\left(1+\frac{|h_{k,i}|^2 p_{k,i}}{N_0}\right)\\ &+\sum_{i=1}^{L}\lambda_i\left(\frac{\mathcal{I}^{\text{th}}}{\ln(p_\epsilon)}+\sum_{k=1}^{K}a_{k,i}b_i\frac{p_{k,i}}{d_k^{\eta}}\right)\\ &+\sum_{k=1}^{K}\rho_k\left(P_k-\sum_{i=1}^{L}a_{k,i}p_{k,i}\right)\end{aligned} \tag{22}$$

where λ_i and ρ_k are Lagrangian coefficients. This problem is in the form of mixed-integer programming problem, which resembles a general resource allocation problem of OFDMA systems. Unlike the general OFDMA resource allocation problem, the above problem additionally needs to consider the interference constraint when performing the power allocation, which makes the problem even more challenging to obtain the optimal solution.

4.1.1 Proposed approach: Solving (20) optimally requires to determine user selection and power allocation at the same time, which give $p_{k,i}$ and $a_{k,i}$, respectively. To solve (20) with a reduced complexity, we propose a simple algorithm that decouples user selection and power allocation, where we select $a_{k,\,i}$ and $p_{k,\,i}$ with the highest capacity in an iterative manner until all the subchannels are allocated. The goal of the algorithm is to achieve the maximum capacity by a simple procedure of user selection and power allocation. Note that the user with the maximum SNR for a subchannel may not always offer the highest capacity in the uplink case because of the individual power constraint. To find out the subchannel with the highest capacity, the capacity per subchannel per user needs to be re-calculated every time a subchannel is allocated to a user.

Each SU performs cap-limited waterfilling [28] for all the subchannels to compute $p_{k,i}$, which is the power allocated for the ith subchannel by the kth user. Using the allocated power, the ergodic capacity is calculated by $C_{k,i} = \log_2(1+p_{k,i}|h_{k,i}|^2/N_0)$ for $k \in \mathcal{K}$ and $i \in \mathcal{U}$, where $\mathcal{K} = \{1, \ldots, K\}$ and $\mathcal{U} = \{1, \ldots, L\}$. Then, the subchannel and the user indices that provide the maximum capacity are selected by

$$\{k^*, i^*\} = \arg\min_{k\in\mathcal{K},i\in\mathcal{U}} C_{k,i} \tag{23}$$

where $\mathcal{U}$ is denoted by the set of unallocated subchannels. The indicator vector for the i*th subchannel is configured as $a_{k,i^*} = 1$, for $k = k^*$, and $a_{k,i^*} = 0$, for other $k \in \mathcal{K}$. This implies that the i*th subchannel is solely allocated to the k*th user and the set of unallocated subchannel has to be adjusted as $\mathcal{U} = \mathcal{U} - \{i^*\}$. In addition, all the users except the k*th user need to re-run cap-limited waterfilling algorithm to avoid power allocation to the i*th subchannel. Once $p_{k,\,i}$ for all ks and is are recalculated, the capacity is again computed and then a new pair of $\{k^*,\ i^*\}$ for the maximum capacity is selected. This procedure continues until all the subchannels are allocated and $\mathcal{U}$ is empty.

Let $\mathcal{U}_{\text{p}}$ denotes the set of subchannels occupied by the PU and $\mathcal{U}_{\text{c}} = \mathcal{U} - \mathcal{U}_{\text{p}}$ is the set of interference-free subchannels. It is assumed that $\mathcal{U}_{\text{p}}$ and $\mathcal{U}_{\text{c}}$ are already known by spectrum sensing. Thanks to the selection of the SU with the highest capacity for each subchannel. Substituting $a_{k,i}$ and b_i, (22) can be simplified, for each k, to

$$\begin{aligned}\mathcal{L} = &\sum_{i=1}^{L}\log_2\left(1+\frac{|h_{k,i}|^2 p_{k,i}}{N_0}\right)+\rho_k\left(P_k-\sum_{i=1}^{L}p_{k,i}\right)\\ &+\sum_{i=1}^{L}\lambda_i\left(\frac{\mathcal{I}^{\text{th}}}{\ln(p_\epsilon)}+\frac{p_{k,i}}{d_k^{\eta}}\right)\end{aligned} \tag{24}$$

From this, the optimal transmit power can be obtained as

$$p_{k,i} = \left[\frac{d_k^{\eta}}{\lambda_i+\rho_k d_k^{\eta}}-\frac{N_0}{|h_{k,i}|^2}\right]^+, \quad 1 \le i \le L \tag{25}$$

where $[x]^+ = \max\{x, 0\}$. It is clear that $\lambda_i = 0$ for $i \in \mathcal{U}_{\text{c}}$. Therefore (25) can be simplified as

$$p_{k_i,i} = \begin{cases}\left[\dfrac{1}{\rho_k}-\dfrac{N_0}{|h_{k,i}|^2}\right]^+, & i \in \mathcal{U}_{\text{c}}\\ \min\left(\left[\dfrac{1}{\rho_k}-\dfrac{N_0}{|h_{k,i}|^2}\right]^+, \dfrac{\mathcal{I}^{\text{th}}d_k^{\eta}}{\ln(p_\epsilon)}\right), & i \in \mathcal{U}_{\text{p}}\end{cases} \tag{26}$$

where the water level for the kth SU is shown as

$$\frac{1}{\rho_k} = \frac{1}{|\mathcal{U}_k|}\left(P_k-\sum_{i\in\mathcal{S}_k}\frac{\mathcal{I}^{\text{th}}d_k^{\eta}}{\ln(p_\epsilon)}+\sum_{i\in\mathcal{U}_k}\frac{N_0}{|h_{k,i}|^2}\right) \tag{27}$$

where $|\mathcal{U}_k|$ denotes the size (number of elements) of the set $\mathcal{U}_k$, and $\mathcal{S}_k$ is the set of subchannels for the kth user satisfying the condition

$$\frac{1}{\rho_k}-\frac{N_0}{|h_{k,i}|^2} > \frac{\mathcal{I}^{\text{th}}d_k^{\eta}}{\ln(p_\epsilon)}$$

Note that (26) is a combination of the conventional waterfilling and the cap-limited waterfilling both with the common water level. The proposed uplink power and subchannel allocation algorithm is given in Fig. 8.

5 Numerical and simulation results

Extensive simulations are performed, where 20 SUs attempt to share a total of 64 subchannels with a PU. The SUs are randomly (or uniformly) located inside a circle with the radius of 1 km and the secondary base station is positioned at the centre, while a PU is

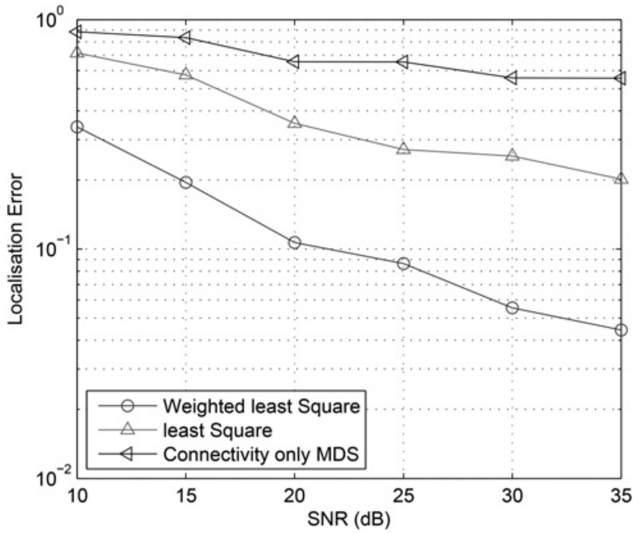

Fig. 2 *Localisation error against SNR (dB)*

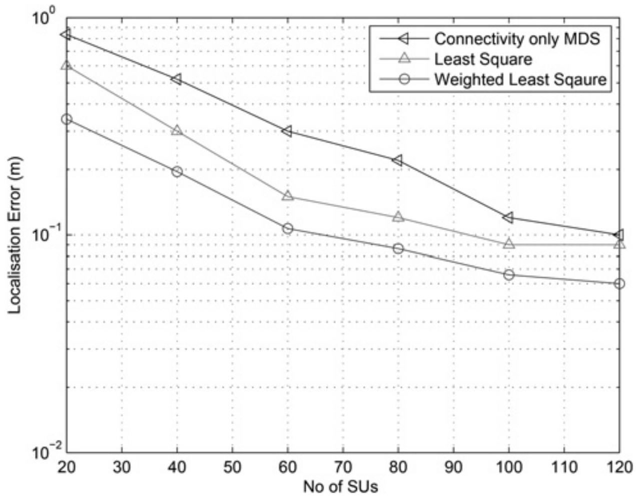

Fig. 3 *Localisation error against number of SUs*

located randomly inside a co-centric circle of radius 8 km. This is a practical scenario with non-identically distributed users in a cellular environment.

Fig. 2 compares the localisation error (LE) of the proposed approach to common least square solution and connectivity-based multidimensional scaling (MDS), and the LE is defined as

$$\text{LE} = \sqrt{(\hat{x}_\text{p} - x_\text{p})^2 - (\hat{y}_\text{p} - y_\text{p})^2} \tag{28}$$

where $\hat{x}_\text{p}$ and $\hat{y}_\text{p}$ are the estimated two-dimensional coordinates of PU. It is clear from the figure that the proposed approach has better accuracy; further the accuracy of the proposed algorithm improves at higher SNR. We have analysed the impact of number of SUs on the localisation accuracy and it can be seen that increasing the number of SUs improves the localisation accuracy, as shown in Fig. 3. We have compared the performance of WLS, LS and connectivity-based MDS against the localisation accuracy, and studied their evolution with the number of SUs. The results are shown in Fig. 3 that the WLS method provides the best performance for all number of SUs, compared to the LS and connectivity-based MDS. Furthermore, we have evaluated the performance of WLS by varying the PU and SUs circle size, as shown in Figs. 4 and 5, respectively. It can be seen in Fig. 4 that

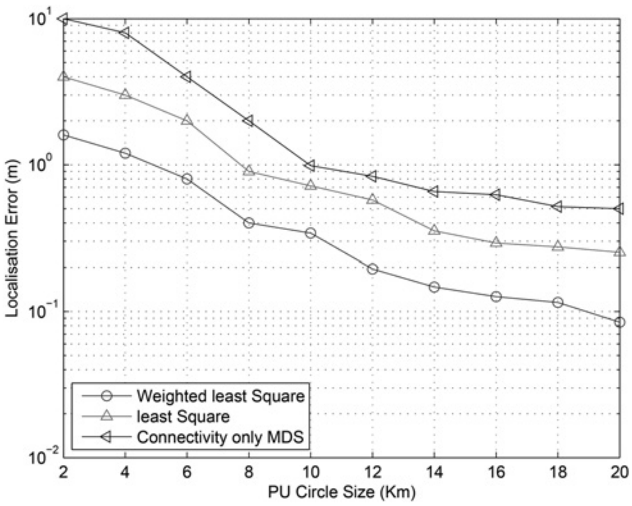

Fig. 4 *Localisation error against PU circle size*

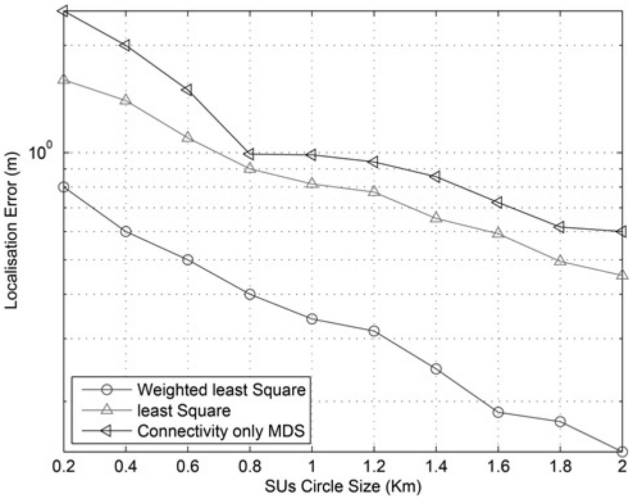

Fig. 5 *Localisation error against SU circle size*

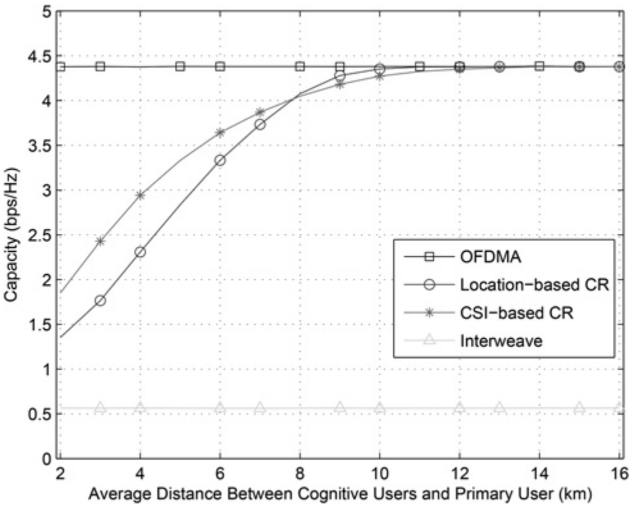

Fig. 6 *Ergodic capacity of the resource allocation algorithm with location information*

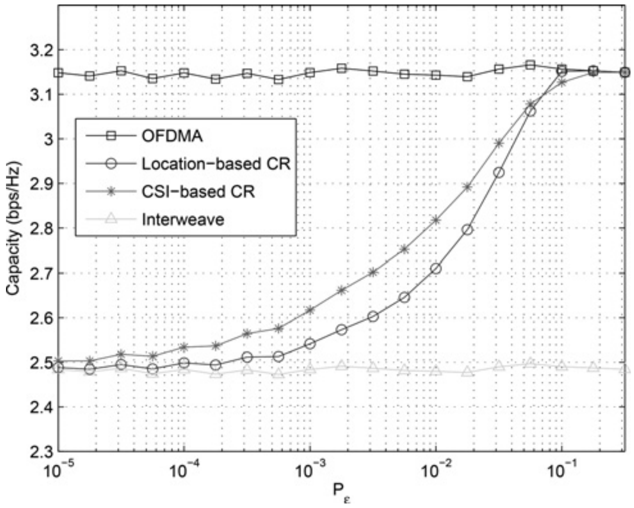

Fig. 7 *Average uplink capacity of various algorithms as a function of p_ε when the PUs and the SUs are randomly located within the cell radius of 8 km*

increasing the PU circle size improves the localisation accuracy because the SUs will receive greater PU signal energy and more number of SUs will contribute to the localisation of PU. Fig. 5 shows that varying the SU's circle size have impact on localisation accuracy. As the SU's circle size increases, SUs within the PU range will receive much higher energy, thereby improving the final localisation accuracy.

Fig. 6 shows the ergodic capacity of the CR systems as a function of average distance between the cognitive base station and PU when LI is used. For comparison purposes, the capacity when CSI of the interference link is assumed to be available is also plotted. As shown in the figure, the capacity loss compared to the CSI-based algorithm is not significant, which indicates that the proposed algorithm using location information is effective and achieves near-optimal capacity. Note that the CSI of the interference link is difficult to obtain, if not impossible, in practical CR systems. Two other scenarios are also plotted for comparison: a regular OFDMA (no PU is present and thus there is no concern about the interference) and an interweave scenario where SUs avoid the subchannels that are occupied by PU (i.e. the cognitive users can only use the subchannels that are free of interference).

Fig. 7 shows the impact of maximum allowable probability of violation for the interference constraint, denoted by p_ε, on the average uplink capacity of the proposed algorithm, with LI under a random spatial distribution of SUs. As shown in the figure, for lower p_ε, stronger protection would be put in place for the PU, and therefore the SUs tend to avoid transmitting over the subchannels occupied by the PUs, which eventually resembles the interweave scheme.

6 Conclusion

This paper introduced an uplink resource allocation algorithm for OFDMA-based CR systems based on the LI of the PU. The localisation of the PU is performed by estimating the pathloss exponent and the transmit power of the PU with a minimum mean square error criterion. Then, the interference to the PU is estimated using the distances between the PU and the SUs instead of using CSI of the interference link. The algorithm also considers the interference violation probability, since the interference constraint needs to be satisfied in a probabilistic (or a stochastic) manner because of Rayleigh fading channels of the interference link. The numerical and simulation results show that the proposed algorithms achieve a near-optimal capacity even without CSI of the interference link (see Fig. 8).

Algorithm 1

```
initialise $\mathcal{U} \Leftarrow \{1, \cdots, L\}$, $\mathcal{U}_p \Leftarrow \{\}$, and $\mathcal{U}_c \Leftarrow \mathcal{U}$
for $k = 1$ to $K$ do
  $\mathcal{U}_k \Leftarrow \mathcal{U}$, and $\mathcal{S}_k \Leftarrow \{\}$
end for
repeat
  for $k = 1$ to $K$ do
    repeat
      compute $\rho_k$ using (27), and $i \Leftarrow 1$
      while $i \in \mathcal{U}_k$ do
        $p_{k,i} \Leftarrow \frac{1}{\rho_k} - \frac{N_0}{|h_{k,i}|^2}$
        if $p_{k,i} < 0$ then
          $p_{k,i} \Leftarrow 0$, $\mathcal{U}_k \Leftarrow \mathcal{U}_k - \{i\}$, and $i \Leftarrow 0$
        else
          if $p_{k,i} > \frac{\mathcal{I}^{th}_{n_{k,i},i} d^{\eta}_{k,n_{k,i}}}{\ln(p_\epsilon)}$ then
            $p_{k,i} \Leftarrow \frac{\mathcal{I}^{th}_{n_{k,i},i} d^{\eta}_{k,n_{k,i}}}{\ln(p_\epsilon)}$, $\mathcal{U}_k \Leftarrow \mathcal{U}_k - \{i\}$, $\mathcal{S}_k \Leftarrow \mathcal{S}_k + \{i\}$, and $i \Leftarrow 0$
          else
            $i \Leftarrow i + 1$
          end if
          $C_{k,i} \Leftarrow \log_2\left(1 + \frac{p_{k,i}|h_{k,i}|^2}{N_0}\right)$
        end if
      end while
    until $i = |\mathcal{U}_k| + 1$
  end for
  $\{k^*, i^*\} \Leftarrow \arg\max_{k \in \mathcal{K}, i \in \mathcal{U}} C_{k,i}$, and $\mathcal{U} \Leftarrow \mathcal{U} - \{i^*\}$
  for $k = 1$ to $K$ do
    if $k \neq k^*$ then
      $\mathcal{U}_k \Leftarrow \mathcal{U}_k - \{i^*\}$
    end if
  end for
until $|\mathcal{U}| = 0$
```

Fig. 8 *Proposed uplink resource allocation*

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