Fairness and throughput enhancement based resource allocation scheme for underlay cognitive radio networks

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Abstract. Acquiring good throughput and diminishing interference to primary users (PU) are the main objectives for secondary users in a cognitive radio (CR) network. This paper proposes a centralized subcarrier and power allocation scheme for underlay multi-user orthogonal frequency division multiplexing considering the rate loss and the interference those the PU can tolerate. The main purpose of the proposed scheme is to efficiently distribute the available subcarriers among cognitive users to enhance both the fairness and the throughput performance of the cognitive network while maintaining the QoS of primary users. Simulation results show that the proposed scheme achieves a significantly higher CR network throughput than that of the conventional interference power constraint (IPC) based schemes and provides a significantly enhanced fairness performance. Also, contrary to the conventional IPC based schemes, the proposed scheme is able to significantly increase the achieved throughput as the number of CR users increases.

Keywords. Cognitive radio; OFDM; resource allocation; spectrum sharing; interference constraints; fairness.

1. Introduction

As the wireless spectrum resources are not used to its full potential, and that stands as a barrier before the new techniques applications. So as a new paradigm, CR has been vastly used to enhance the wireless spectrum utilization effectively [1]. SUs have the ability in perceiving and detecting the changes of the dynamic environment for the wireless spectrums, and make the passive spectrum available to the cognitive users. Then SUs can worthily fill the passive spectrum left by the Primary Users (PUs).

In CR networks, PUs and SUs coexist, CR networks provide the capability for the SUs for sharing the wireless channel with the PUs under the interference constraint. There are three modes for CR transmissions: interweaved, overlay and underlay [2]. In the interweaved mode, the SU transmitter implement spectrum sensing to find spectrum holes before it can access the spectrum. The other two modes permit simultaneous SU and PU transmissions. The difference is that the overlay mode presumes perfect PU knowledge at the SU transmitter, whereas the underlay mode presumes a loosely coupled relationship or no cooperation at all between PUs and SUs [2].

As an ideal alternative technology for realizing CR systems, orthogonal frequency division multiplexing (OFDM), due to its adaptability and flexibility with its underlying spectrum shaping capabilities, can improve

significantly the execution of CR systems [3],[4]. IPC is always imposed on each subchannel to guarantee the SUs not causing hurtful interference to the PUs in underlay mode of OFDM-based CR network. So the research of capacity maximization under power control has received lots of interest. The authors [5] proposed a power allocation strategy to optimally maximize the rate of SUs under both the IPC and the rate loss constraint. Authors in [6] maximized the ergodic throughput of a secondary user under the rate loss constraint for primary users by investigating both power allocation and sensing time schemes. Authors [7] considered power allocation in OFDM based underlay CR networks under a given limited transmit power at the SU's transmitter, such that the CR network throughput can be maximized, and the tolerable interference to the PU can be kept within an objective outage probability level. In [8], the authors investigated a power allocation algorithm on the subchannel assignment for downlink OFDM-based cognitive network under both the maximum transmit power constraint and the interference power outage constraint to maximize the utilization of the spectrum and provide proportional fairness to the SUs. In [9], they proposed a new centralized power allocation technique considering departure and arrival of primary users that maximizes total capacity for the cognitive user while regarding an average interference constraint. Authors [10] have proposed sub-optimal schemes for subcarrier allocation with associated power loading technique for the OFDM- CR systems. In [11], a power allocation grouping scheme for orthogonal

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frequency division multiplexing (OFDM)-based Cognitive Radio systems is proposed that can improve capacity while the interference power for primary user receivers stays at constant level. Authors in [12], proposed a joint subcarrier and power allocation algorithm for multiuser orthogonal frequency division multiplexing (MU-OFDM) cognitive radio (CR) systems, where the peak power constraint is used to protect the primary user using a proposed low-complexity method to update the water level on the water filling algorithm.

The contributions of this paper are as follows. We consider a spectrum underlay CR network where an (MU-OFDM)-based CR system coexists with an OFDMA-based primary system. Instead of using the conventional resource allocation method based on IPC and rate loss constraint to protect PU, here we propose a new resource allocation scheme which consider the above constraints but enhances both the fairness and throughput performance of the CR network. The proposed subcarrier allocation algorithm is based on allocating the subcarrier to the best CR user that has the minimum interference channel gain with a proposed fairness constraint, and hence can transmit with a highest power and achieve the utmost throughput while providing improved fairness performance. In addition, we adopt a new power allocation algorithm that will aid the proposed subcarrier allocation algorithm in enhancing the throughput performance.

The remainder of this paper is organized as follows. Section 2 describes the system model and section 3 introduces the proposed resource allocation scheme. Simulation results are proved in section 4 and the conclusions are provided in section 5.

2. System model

2.1 System architecture and assumptions

We consider the problem of the resource allocation on downlink of an MU-OFDM secondary system in which the secondary base station is communicating with MSUs using N sub-channel belonging to an OFDMA primary system with K primary users as long as no harmful interference occurs to these PUs. This kind of spectrum sharing is known as underlay sharing. Also, assume the background noise is additive white Gaussian noise (AWGN), and the noise power of each subcarrier is denoted by N_0 .

Let g_i be the channel power gain between the primary transmitter (PU-Tx) and receiver (PU-Rx) at subcarrier i (see figure 1), U_i be the transmit power of PU allocated to subcarrier i , then the transmission rate of PU_k (the throughput of PU_k) in the absence of SU is given by:

$$R_k^p = \frac{1}{N} \sum_{i \in L_k} \log_2 \left(1 + \frac{g_i U_i}{N_0} \right), \quad \forall k \in \{1, 2, \dots, K\}. \quad (1)$$

Where L_k is the subcarriers set allocated to PU_k .

Figure 1. Channel model at subcarrier $i, i \in \{1, \dots, N\}$.

Let P_i be the transmit power of SU allocated to subcarrier i , and h_i be the channel power gain between the secondary transmitter (SU-Tx) and PU's receiver, due to SU's transmission, for any $k \in \{1, 2, \dots, K\}$, then the average rate of PU_k (the throughput of PU_k) in the presence of SU is given by:

$$R_k^s = \frac{1}{N} \sum_{i \in L_k} \log_2 \left(1 + \frac{g_i U_i}{N_0 + h_i P_i} \right). \quad (2)$$

Let f_i be the channel power gain of the channel between SU's transmitter and receiver at subcarrier i , and let d_i be the channel power gain of the channel between PU's transmitter and SU's receiver at subcarrier i . It is assumed that PU's transmitted signals are Gaussian distributed. Then, the introduced interference to SU by the PU can take the AWGN model with power J_i , where $J_i = d_i U_i$. The achievable rate of SU (the throughput of SU) is then given by:

$$r_s = \frac{1}{N} \sum_{i=1}^N \log_2 \left(1 + \frac{f_i P_i}{J_i + N_0} \right). \quad (3)$$

The last equation shows the relationship between the number of bits loaded on the subcarrier and the transmit power for a given SU when perfect CSI is available at the transmitter.

2.2 Interference power and rate loss constraints [5]

Let Γ_k be the maximum total interference power that PU_k can endure. Then, we can write the constraint of the per user based interference power as

$$\sum_{i \in L_k} h_i P_i \leq \Gamma_k, \quad \forall k \in \{1, 2, \dots, K\}. \quad (4)$$

Let ΔR_k be the maximum rate loss that PU can endure, then only by satisfying the following constraint, SU's transmission is allowed.

$$R_k^p - R_k^s \leq \Delta R_k, \quad \forall k \in \{1, 2, \dots, K\}. \quad (5)$$

The previous constraints are alluded as the PUs' rate loss constraints. If we define

$$R_k \triangleq R_k^p - \Delta R_k, \quad \forall k \in \{1, 2, \dots, K\}. \quad (6)$$

then we can rewrite the rate loss constraints as

$$R_k^s \geq R_k, \quad \forall k \in \{1, 2, \dots, K\}. \quad (7)$$

3. The proposed resource allocation scheme

The proposed resource allocation scheme is implemented by two phases. In the first phase, the proposed subcarrier allocation algorithm allocates the subcarrier to the best m CR user that has the minimum interference channel gain h_i , with a proposed fairness constraint to achieve a maximum throughput under IPC over that subcarrier.

The steps of the proposed subcarrier allocation algorithm are as follows:

- Interference channel gains information for all N subcarriers are centrally collected from all CR users.
- Find the minimum interference channel gain detected for each subcarrier.
- Arrange all the subcarriers ascendingly according to the interference channel gain defined on the previous step.
- Set a fairness constraint threshold $\eta \cdot N_{avg}$ which define the maximum number of subcarriers that can be allocated to any CR user during the subcarrier allocation process to enhance the fairness performance.

Where:

$$N_{avg} = N/M; \quad (8)$$

and η is a fairness controlled parameter which is equal to 1 ($\eta = 1$) for a fair subcarrier allocation and greater than 1 ($\eta > 1$) for a partial fair subcarrier allocation.

The relationship between the rate loss constraint and the per subcarrier based IPC [5] is satisfied when

$$\tilde{\Gamma}_k = N_0 \left(2^{K\Delta R_k/|L_k|} - 1 \right) \quad (9)$$

where $\tilde{\Gamma}_k$ is the maximum interference power that each subcarrier of PU_k can endure and ΔR_k is the maximum rate loss that can be endured by the PU where the relationship between the PU throughput and its SNR is shown in equations (1) and (2).

- The CR system selects the best CR user that has the minimum interference channel gain h_i for each subcarrier $i, i \in \{1, \dots, N\}$ with the fairness constraint threshold $\eta \cdot N_{avg}$ defined previously. From the IPC condition shown next in equation (10), we define the transmitted power P_i that every SU can send over each subcarrier i

$$h_i P_i \leq \Gamma_k, \quad \forall i \in L_k \quad (10)$$

Choosing a minimum interference channel gain lead to maximize the value of transmitted power P_i and then enhance the throughput of the SU according to equation (3).

All the previous steps are summarized in figure 2.

In the second phase, a new power allocation algorithm is proposed to efficiently manage and distribute the power budget of each SU over its allocated subcarriers.

Phase 1: Subcarrier Allocation

INPUT $M, N, K, \mathbb{E}\{g_i\} = \mathbb{E}\{f_i\} = 1, \mathbb{E}\{h_i\} = \mathbb{E}\{d_i\} = 0.1, N_{avg} = N/M$, CSI information, and power budget for each CR = P_a ;

for $m = 1:M$

for $i = 1:N$

Find the minimum value of h for each subcarrier;

Put the found values of h on a vector $H = [h_1, h_2, \dots, h_N]$;

Rearrange the elements of vector H ascendingly;

end for

Initialize $\beta = 1, \forall \beta \in H$ and $\eta = 1$;

if number of allocated subcarriers to user $m < \eta \cdot N_{avg}$ **then**

Allocate subcarrier β to user m ;

else

$\beta = \beta + 1$;

end if

Update $\eta = \eta + 0.1$;

Assign power P_i for each subcarrier i according to $h_i P_i \leq \Gamma_k, \forall i \in L_k$ [5].

end for

OUTPUT The set $L_m^s = [1, 2, \dots, Y]$ of subcarriers allocated to each secondary user m .

Figure 2. The proposed subcarrier allocation algorithm.

Phase 2: Power Allocation

INPUT $M, L_m^s = [1, 2, \dots, Y]$, Power budget for each CR user $= P_a$

for $m = 1:M$

for $z = 1:Y$

$$\omega_y = \frac{f_{m,y}}{\sum_{t=0}^Y f_{m,t}}; \forall y \in L_m^s.$$

Calculate the power of each y as $P_y = \omega_y P_a$;

The final power for each subcarrier is $P_{sub} = \min(P_y, P_i)$; where P_i is calculated through phase 1.

end for

end for

Define SU's throughput as: $r_s = \frac{1}{N} \sum_{i=1}^N \log_2 \left(1 + \frac{f_i P_{sub}}{J_i + N_0} \right)$.

OUTPUT

$$\text{Fairness index} = \frac{\left(\sum_{e=1}^M r_{s,e} \right)^2}{M \cdot \left(\sum_{e=1}^M (r_{s,e})^2 \right)}, \forall e \in \{1, \dots, M\}.$$

Figure 3. The proposed power allocation algorithm.

We suppose that each SU has been allocated to a set L_m^s of subcarriers. Assume the maximum number of subcarriers inside this set is denoted by Y .

- The amount of power that will be allocated to each subcarrier on the set L_m^s depends on the direct channel gain for the SU over this subcarrier to enhance the total CR network throughput.
- Let the power budget for every SU_m is P_a , then the allocated power per subcarrier y will be $P_y = \omega_y P_a$

where

$$\omega_y = \frac{f_{m,y}}{\sum_{t=0}^Y f_{m,t}}; \quad \forall y \in L_m^s \quad (11)$$

Where L_m^s is the subcarriers set allocated to each SU.

Thus, the weight ω_y can be defined as the ratio of SU's direct channel gain for the current subcarrier y to the sum of the same SU's direct channel gains for all the set of subcarriers allocated to that SU.

- Finally, with applying the IPC constraint, the allocated subcarrier power will be $P_{sub} = \min(P_y, P_i)$ for each subcarrier and the equation of the throughput achieved by the SU in equation (3) can be rewritten as

$$r_s = \frac{1}{N} \sum_{i=1}^N \log_2 \left(1 + \frac{f_i P_{sub}}{J_i + N_0} \right). \quad (12)$$

The fairness index that measure the fairness of the throughput distribution among the secondary users can be calculated as

$$\text{Fairness index} = \frac{\left(\sum_{e=1}^M r_{s,e} \right)^2}{M \cdot \left(\sum_{e=1}^M (r_{s,e})^2 \right)}, \quad \forall e \in \{1, \dots, M\}. \quad (13)$$

Where r_s is the SU throughput.

All the previous steps are summarized in figure 3.

4. Simulation results

4.1 Performance of the proposed scheme under perfect channel state information

In this section, several examples are displayed to verify the effectiveness of the proposed resource allocation strategy. In these simulation examples, we assume that all the

included channels (i.e., the secondary link, the primary link, and the interference links) are Rayleigh distributed. So, the channel power gains of these channels are exponentially distributed. MATLAB® is used to develop the simulation program for the proposed scheme, and all the CR network parameters and equations are considered on the developed MATLAB code to assess the performance of the proposed scheme compared to the conventional IPC based scheme. Where the conventional IPC based scheme proposed in [5], illustrates a power allocation algorithm with random subcarrier allocation under a new primary transmission protection criteria. The simulation results are displayed in this part are taken out by averaging over 10^6 independent simulation runs. The average channel power gains for the secondary link f_i and the primary link g_i are presumed to be 1, i.e., $\mathbb{E}\{g_i\} = \mathbb{E}\{f_i\} = 1, \forall_i$. The average channel power gain for the interference links is presumed to be 0.1, i.e.,

$\mathbb{E}\{h_i\} = \{d_i\} = 0.1, \forall_i$. Moreover, we presume that the system contains a single primary user and multi-secondary users. The PU shares 128 subcarriers with SNR changes from 1 to 30 dB. It is also presumed that the primary system adopts equal power allocation over its subcarriers. The noise power on each subcarrier is presumed to be identical, and equal to 1, i.e., $N_o = 1$. The cognitive radio network simulation parameters are summarized in table 1.

Figure 4 shows the achieved throughput by the secondary network as a function of the SNR received from the primary user at secondary power budget $P_a = 20$ dB, 10% PU rate loss, $\eta = 1.2$, and various number of SUs. As expected, the throughput of the secondary network significantly decreases as the PU's SNR becomes higher. The reason behind is that the significant increase of the interference produced by the high PU's power on the SU as in equation (3). The figure also reveals that the secondary network throughput achieved by the proposed scheme is significantly higher than that of the conventional scheme and it significantly increases as the number of SUs increases. This is because, as the number of SUs increases, the opportunity that the selected SU has a low interference channel gain is improved which improves the efficiency of the proposed algorithm on allocating the subcarrier to the best SU.

The throughput of the primary network as a function of PU's SNR is presented in figure 5. It is observed that the proposed scheme maintains the PU's QoS as the conventional scheme by allowing the primary network to achieve the same throughput. This means that the proposed scheme does not produce a harmless interference on the PU since it allocates the subcarriers to the SU that has the

Table 1. The description of the CR network parameters.

Parameter	Value or description
Channel model	Rayleigh distributed
Mean of g_i	1
Mean of f_i	1
Mean of d_i & h_i	0.1
No. of primary users K	1
No. of secondary users M	4, 8, 16
No. of subcarriers N	128
Primary user power budget	1–30 dB
Secondary user power budget	20 dB
Maximum rate loss of primary user	10%

Figure 4. The secondary network throughput (bit/sec/Hz) versus the PU SNR (dB) at $\eta = 1.2$ with different numbers of SUs.

Figure 5. The primary network throughput (bit/sec/Hz) versus the PU SNR (dB) at $\eta = 1.2$ and different numbers of SUs.

minimum interference channel gain (i.e., the lowest interference effect on PU).

Figure 6 presents the fairness performance of the proposed resource allocation scheme as a function of PU's SNR at a $\eta = 1.2$. As observed from figure, the fairness index slightly decreases as the PU's SNR increases as seen in equations (12), (13). Also, the fairness index increases with decreasing the number of SUs, because the average

number of subcarriers allocated to each SU, N_{avg} under the same total subcarriers N will be increased. This will give the opportunity to each individual SU to experience different subcarrier interference channel gains and hence, improving the fairness performance. In addition, the proposed scheme achieves a significantly high fairness index which is slightly lower than that of the conventional scheme. In the conventional scheme, the number of

Figure 6. Fairness index for CRs with the primary user SNR (dB) at SU power budget $P_a = 20$ dB, $\eta = 1.2$ and different number of SUs.

Figure 7. The secondary network throughput (bit/sec/Hz) versus η at SU power budget $P_a = 20$ dB and different numbers of SUs.

allocated subcarriers per SU is approximately equal to N_{avg} , which leads to its good fairness performance, and this case is equivalent to $\eta = 1$ for the proposed scheme.

Figure 7 presents the relation between η and the CR network throughput at PU's SNR = 2 dB. The figure shows that the CR throughput of the proposed scheme significantly increases with the increase of η and when η becomes greater than 1.4, the CR throughput is approximately saturated to its maximum values with no significant increase. This is because as η increases, the number of good subcarriers that can be allocated to a specific SUs will be larger than N_{avg} which enable the proposed scheme to efficiently allocate the subcarriers to the best SUs which can have the minimum interference channel gain under a more relaxed fairness constraints.

Figure 8 shows the effect of changing η on the fairness index of the CR network at PU's SNR = 2 dB. It is observed that at $\eta = 1$, the fairness index of the proposed scheme is approximately the same as that of the conventional scheme. In addition, the fairness index of the proposed scheme slightly decreases as η increases ($\eta > 1$) because the number of allocated subcarriers to each CR user will not be the same. So, some SUs have more allocated subcarriers than the others which slightly reduces the fairness index.

Table 2 gives a comparison between the proposed scheme with, without applying fairness constraint and the conventional scheme. The results reflect that the throughput of the secondary network achieved by the proposed scheme with applying fairness constraint scheme at $\eta = 1.3$ approximately converges to the maximum values achieved

without applying fairness constraint and significantly higher than the conventional one. On the other hand, the proposed scheme with applying fairness constraint scheme at $\eta = 1.3$ provides a significantly enhanced fairness performance which approximately converges with that of the conventional scheme and significantly higher than that of the proposed scheme without applying fairness constraint.

4.2 Performance of the proposed scheme under imperfect channel state information

Most existing works assume that h_i is perfectly known. However, h_i is imperfect, which is an important scenario for CR systems. A channel estimation is done by (SU-Rx) to estimate the SU-PU interference channel gain, denoted by h_i . Existence of channel estimation errors is assumed, i.e.,

$$h_i = \hat{h}_i + e_{EST}, \quad \forall i \in \{1, 2, \dots, N\} \quad (14)$$

where $\hat{h}_i$ is the estimated channel gain and e_{EST} is the estimation error. Furthermore, we assume that estimation error e_{EST} is a uniform random distribution vector with zero-mean and variance σ_e^2 which is assumed here to be 0.5.

Figure 9 shows the achieved throughput by the secondary network as a function of the received SNR from the primary user at secondary power budget $P_a = 20$ dB, 10% primary rate loss, $\eta = 1.2$, and $M = 8$ SUs. As expected, CR's throughput significantly decreases as PU's SNR

Figure 8. The fairness index in CR network versus η at SU power budget $P_a = 20$ dB, and different numbers of SUs.

Table 2. The throughput of the secondary network by the proposed scheme with applying fairness constraint scheme at $\eta = 1.3$, without applying fairness constraint and finally for the conventional scheme at $M = 16$ CR.

Different schemes	Throughput (bit/sec/Hz)	Fairness index
Conventional scheme	1.3104	0.8411
Proposed scheme without fairness constraint	2.6692	0.6353
Proposed scheme with fairness constraint at $\eta = 1.3$	2.4403	0.8283

Figure 9. The secondary network throughput (bit/sec/Hz) versus the PU SNR (dB) at $\eta = 1.2$ with $M = 8$ SUs under both perfect and imperfect CSI.

increases due to the significant increase of the interference produced by the high PU's power on the SU as in equation (3). The figure also demonstrates that the degradation occurred in the throughput due to the imperfect CSI is

small. This reflects the robustness of the proposed scheme in the real environment.

Figure 10 draws the relation between η and the CR network throughput at PU's SNR = 12 dB. The

Figure 10. The secondary network throughput (bit/sec/Hz) versus η at SU power budget $P_a = 20$ dB and $M = 8$ under both perfect and imperfect CSI.

Figure 11. The fairness index in CR network versus η under perfect and imperfect CSI.

figure shows that the CR throughput by the proposed resource allocation scheme significantly increases with increasing η . When η becomes ≥ 1.4 , the CR throughput is approximately saturated to its maximum values. The figure also demonstrates that the proposed scheme significantly outperforms the conventional scheme especially for $\eta \geq 1.4$. The degradation on the proposed scheme due to the imperfect channel statement is small especially for the usable range of the fairness controlled parameter ($\eta < 1.4$).

Figure 11 shows the effect of changing η on the fairness index of the CR network at PU's SNR = 12 dB. It is observed that the fairness index of the proposed scheme is slightly lower than that of the conventional scheme and slightly decreases as η increases. It is worth to mention that the proposed scheme achieves its maximum throughput at $\eta = 1.4$ which means that a slight degradation in the fairness index is expected. In addition, it is clear that the imperfect CSI has no effect on the fairness performance of both schemes.

5. Conclusion

The proposed centralized subcarrier and power allocation scheme for underlay MU-OFDM in this paper efficiently distributes the available subcarriers among cognitive users and enhances both the fairness and the throughput performance of the cognitive network while maintaining the QoS of primary users. Simulation results reflect that the proposed scheme achieved a significantly higher CR network throughput than that of the conventional IPC based schemes and provides significantly enhanced fairness performance. Through applying the fairness constraint, the proposed algorithm is still robust in enhancing the throughput performance, while achieving a significant high fairness performance. Also, to the contrary of the conventional IPC based schemes, the proposed algorithm is able to significantly increase the achieved throughput as the number of CR users increases. In addition, the proposed scheme proved its robustness through both the perfect and imperfect channel state information.

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