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Price-based spectrum sharing and rate allocation in the downlink of multihop multicarrier wireless networks

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Abstract: The author addresses the problem of subcarrier sharing with discrete rate allocation in the downlink of multicell and multihop orthogonal frequency division multiple access networks. The co-channel interference makes the problem computationally intractable. The author therefore models the problem as a non-cooperative game among the transmitting nodes with smaller scale problems. Each problem is solved using dual decomposition. Moreover, to mitigate the degradation effect of co-channel interference in this game, the author additionally proposes a price-based game. This game charges the nodes for their transmit power on subcarriers. Numerical results demonstrate that price-based game outperforms the non-cooperative game as a result of distributed interference avoidance. In addition, both the games with subcarrier sharing achieve higher sum-rate in comparison with resource allocation schemes with no subcarrier sharing.

1 Introduction

Next generation wireless networks are expected to provide ubiquitous and high date rate transmission. The integration of multicarrier transmission in the form of orthogonal frequency division multiple access (OFDMA) and multihop transmission is a promising technique towards this ambition. OFDMA mitigates frequency selectivity fading of the broadband channel by dividing the bandwidth into a set of non-interfering narrowband subcarriers. On the other hand, multihop transmission extends the coverage area of the network by overcoming the high path loss. This technology is cost efficient compared with increasing the number of base stations (BSs) [1].

To realise the advantages of multihop OFDMA networks, it is necessary to derive efficient resource allocation schemes for dynamic subcarrier assignment and adaptive power allocation. Because of the multihop spatial diversity and the demand of high data rate transmission, it is beneficial to use aggressive frequency reuse, that is, all the OFDMA subcarriers are shared among the serving nodes [2]. The co-channel interference caused by the subcarrier sharing makes the resource allocation to nodes more coupled and difficult to manage. Moreover, in networks with single-radio nodes, it is not possible for nodes to receive and transmit on a subcarrier simultaneously. This limitation in the functionality of nodes raises the concern of conflicting links [3]. This consideration can also increase the complexity of resource allocation.

In [4–6], suboptimal centralised algorithms in multihop OFDMA networks are proposed with and without subcarrier sharing, respectively. These algorithms suffer from the huge amount of signalling as a result of feeding back the channel state information throughout the network to a central controller and forwarding the scheduling decisions. One alternative approach is to extend the conventional single-hop scheduling schemes [7, 8] to multihop networks. This approach partitions the users as well as the resources into clusters around the serving nodes and performs the resource allocation accordingly [9–11]. However, it fails to manage the interference caused by the co-channel transmissions, in the case of subcarrier sharing.

Game theory is a mathematical tool to model the interactions among self-interested rational players [12]. Each player in the game aims to maximise its own 'pay-off function' in a distributed fashion. The game settles down in a Nash equilibrium (NE), if one exists. As a result of its distributed structure, there has been an increasing interest in employing the game theory for power control and frequency assignment in wireless networks. In a non-cooperative game, a network node myopically transmits on subcarriers with high power to maximise its own pay-off function, that is, the achieved sum-rate value. Because of the selfish behaviour of the nodes, the resulting NE is not necessarily efficient from the social viewpoint. The co-channel interference generated in these games degrades the network performance significantly. Alternatively, price or tax-based games in which network nodes are charged for their transmit power on subcarriers are highly interested. In [13], a tax-based algorithm for subcarrier sharing among the clusterheads in wireless mesh networks (WMNs) is proposed. Under the assumption of uniform power allocation to subcarriers and continuous rate allocation, it is shown that the proposed algorithm attains a NE. Under the assumption that each node can only transmit on one frequency at a time, a price-based algorithm for frequency selection and power allocation in WMNs has been proposed in [14]. It is shown that this algorithm performs better than the non-cooperative game but not as well as a negotiation-based cooperative algorithm.

Having in mind the discussed limitations and challenges, in this paper, we first model the subcarrier sharing and rate allocation in the downlink of OFDMA networks as an optimisation problem. The model is general in that it includes both multicell and multihop topologies. Unlike the continuous rate in the majority of works in the literature, we consider a finite set of discrete modulation rates on each subcarrier. To manage the conflict links in multihop networks, we second partition the network links into distinct sets, called 'independent sets', in such a way that the links in one set can simultaneously be active on every subcarrier. We allocate disjoint sets of subcarriers to independent sets based on the uniform power allocation. Given the aforementioned link and subcarrier sets, we thirdly consider the problem as a non-cooperative game among the serving nodes to mitigate the high complexity. Owing to the degradation effect of co-channel interference, we finally propose a price-based subcarrier sharing (PBSS) approach to improve the performance of the non-cooperative game. This approach charges the serving nodes for their transmit power so as to render the subcarrier sharing scheme efficient.

The rest of this paper is organised as follows. The system model and problem formulation are described in Section 2. Algorithms for independent set construction and subcarrier assignment are proposed in Section 3. In Sections 4 and 5, non-cooperative game and PBSS are presented, respectively. Performance evaluation is given in Section 6 and the paper is concluded in Section 7.

2 System model and problem formulation

We consider an OFDMA network with a set $\mathcal{K} \triangleq \{i{:}i = 1, \ldots, K\}$ of nodes and a set $\mathcal{L} \triangleq \{ij\}$ of links. Every link ij is the link from transmitting node $i \in I(j)$ to the receiving node $j \in O(i)$, as shown in Fig. 1. $I(j)$ and $O(i)$ are the sets of transmitting and receiving nodes of the links ingoing to and outgoing from the nodes j and i, respectively. Moreover, $\Omega \triangleq \{n{:}n = 1, \ldots, N\}$ is the set of subcarriers to be assigned to the links. The total transmit power at each node i is allocated to the assigned subcarriers to the outgoing links of this node. Allocated rate on each subcarrier is assumed to be in a finite set $\mathcal{Q} \triangleq \{1, \ldots, Q\}$ of modulation rates.

We define $x_{ij}^{n,q}$ as a binary variable, where $x_{ij}^{n,q} = 1$ if subcarrier n is assigned to link ij with modulation rate q,

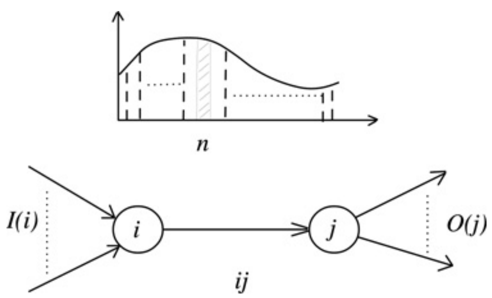

Fig. 1 *Model diagram*

otherwise $x_{ij}^{n,q} = 0$. It is assumed that nodes in the network are not able to both transmit and receive on a given subcarrier at the same time. This constraint is written as

$$\sum_{j\in O(i)} \sum_{q} x_{ij}^{n,q} + \sum_{j\in I(i)} \sum_{q} x_{ji}^{n,q} \le 1 \quad \forall i, n \tag{1}$$

which means that a given subcarrier n can simultaneously be used only on one link ingoing to or outgoing from node i.

Let G_{ij}^n be the channel gain of subcarrier n on link ij and p_i^n is the transmit power of node i on this subcarrier. Under the assumption that each subcarrier can be reused throughout the network, signal-to-interference-plus-noise ratio (SINR)of subcarrier n on link ij is given by

$$\gamma_{ij}^n \triangleq \frac{G_{ij}^n p_i^n}{I_{ij}^n(p_{-i}^n)} \tag{2}$$

where

$$I_{ij}^n(p_{-i}^n) \triangleq \sum_{k=1, k\neq i}^{K} G_{kj}^n p_k^n + \sigma^2$$

Moreover, σ^2 is the noise power and $p_{-i}^n \triangleq \left[p_1^n, \ldots, p_{i-1}^n, p_{i+1}^n, \ldots, p_K^n\right]$ is the vector of all interfering transmit powers. Let T_q be the required SINR to transmit with modulation rate q, that is, $q = \log_2(1 + T_q)$. To be enable to transmit with rate q on subcarrier n over link ij, we need $\gamma_{ij}^n = T_q$ or equivalently $p_i^n = I_{ij}^n(p_{-i}^n)T_q/G_{ij}^n$. Owing to (1), that each subcarrier can only be assigned to at most one outgoing link from i, we come up with

$$p_i^n = \sum_{j\in O(i)} \sum_{q=1}^{Q} x_{ij}^{n,q} I_{ij}^n(p_{-i}^n) T_q / G_{ij}^n \tag{3}$$

Moreover, considering power budget P at every node i, the total transmit power should satisfy

$$\sum_{n=1}^{N} p_i^n \le P \tag{4}$$

The resource allocation problem to maximise the network sum-rate subject to the aforementioned constraints is accordingly presented as

$$\max_{\mathbf{X},\mathbf{P}} \sum_{i=1}^{K} \sum_{j\in O(i)} \sum_{n=1}^{N} \sum_{q=1}^{Q} q x_{ij}^{n,q} \tag{5}$$

$$\text{s.t.} \sum_{j\in O(i)} \sum_{q=1}^{Q} x_{ij}^{n,q} + \sum_{j\in I(i)} \sum_{q=1}^{Q} x_{ji}^{n,q} \le 1 \quad \forall i, n \tag{6a}$$

$$p_i^n = \sum_{j\in O(i)} \sum_{q=1}^{Q} x_{ij}^{n,q} I_{ij}^n(p_{-i}^n) T_q / G_{ij}^n \quad \forall i, n \tag{6b}$$

$$\sum_{n=1}^{N} p_i^n \le P \quad \forall i \tag{6c}$$

where $\boldsymbol{X} = \{x_{ij}^{n,q}\}$ and $\boldsymbol{P} = \{p_i^n\}$ and are vectors of optimisation variables.

Problem (5)–(6) is a mixed integer programming problem with high complexity [15]. Indeed, complexity grows exponentially with the number of nodes, subcarriers and outgoing links. To mitigate this difficulty, we therefore deploy distributed decision making approaches such as game theory in subsequent sections to solve the problem. Although the outcome achieved is expected to be less efficient than a possible centralised optimisation, these approaches are favourable in terms of computational complexity and scalability [16, 17].

3 Independent set construction

As noted in Section 1, one important consideration in the design of resource allocation schemes is not to active conflicting links simultaneously on a subcarrier [3]. In general, a conflict arises between two links when they have a node in common such that this node either is the transmitting node of one link and the receiving node of the other link, or is the receiving node of both links. Consequently, links ij and cd are considered as conflicting links if either $i = d$ or $j = c$ or $j = d$. The consideration of conflicting links has been included in the constraint (6a) of problem (5)–(6). Prior to solve this problem, because of the high complexity of (6a), we aim to address conflict links in the problem and to simplify this constraint by defining an 'independent set' (IS) as follows.

Definition 1: One IS is the set of links such that no two links mutually conflict with each other, that is, all the links in each IS can simultaneously be active on one subcarrier.

To make ISs construction computationally efficient, we here propose a heuristic approach in Fig. 2 Algorithm 1 to partition the network links into distinct ISs. In this algorithm, e is the index of ISs and E is the number of generated ISs since the beginning of the algorithm. Moreover, IsConflict(IS_e, ij) is equal to 1 if there is at least one conflicting link in IS_e with link ij, otherwise it is equal to 0. This algorithm first aims to insert a given link ij into an existing IS in the loop, IS_e, in which there is no a conflicting link with ij. Otherwise, a new IS is generated.

Algorithm 1

set $E = 1$ and $IS_1 = \varnothing$.
for all $ij \in \mathcal{L}$ **do**
  $e = 1$.
  while $IsConflict(IS_e, ij) = 1$ **do**
   $e = e + 1$.
  end while
  if $e \le E$ **then**
   $IS_e = IS_e \cup \{ij\}$
  else
   $E = E + 1$
   set $IS_E = \{ij\}$.
  end if
end for

Fig. 2 *ISs Construction*

Algorithm 2

1: initialise $\Omega_e = \varnothing$ for all e.
2: **for all** n **do**
3: **for all** e **do**
4: set $p_i^n = P/(1 + |\Omega_e|)\forall ij \in IS_e$.
5: compute $u_e^n = \sum_{ij \in IS_e} \log_2(1 + \gamma_{ij}^n)$.
6: **end for**
7: $e^* = \arg\max_e (u_e^k)$.
8: $\Omega_{e^*} = \Omega_{e^*} \cup \{k\}$.
9: **end for**
10: return Ω_e for all e.

Fig. 3 *Subcarrier assignment to ISs*

Once network links have been grouped into ISs, subcarriers are also required to be included into distinct sets; each subcarrier set to be shared within an IS. The reason is that each subcarrier can not be used simultaneously by two ISs. We propose Fig. 3 Algorithm 2 to divide the subcarriers into disjoint sets corresponding to ISs. In this algorithm, Ω_e denotes the set of subcarriers assigned to IS_e and $|\Omega_e|$ is the cardinality of Ω_e. In Step 4, provided that subcarrier n is assigned to IS_e, we allocate equal transmit power to this subcarrier on every $ij \in \mathrm{IS}_e$. Note that p_i^n in Step 4 is an auxiliary power allocation, not the final and desired one. Corresponding to each subcarrier, achieved sum-rate in different ISs are computed in Step 5. In Steps 7 and 8, subcarrier n is assigned to IS_{e^*} for which assigning this subcarrier achieves the highest sum-rate.

Once ISs and their associated subcarrier sets have been determined, each IS can be considered as a subnetwork without conflicting links. Now the network-wide resource allocation problems (5) and (6) can be decomposed into subproblems corresponding to derived ISs., This decomposition simplifies constraint (6a) into the form

$$\sum_{j \in O(i)} \sum_{q=1}^{Q} x_{ij}^{n,q} \le 1 \quad \forall i, n \tag{7}$$

to be considered in Section 4, where the resource allocation problem is to be solved. It is our understanding that with the defined ISs and a disjoint set of subcarriers associated with each IS, subcarrier reuse/sharing among ISs and therefore inter IS interference is avoided. However, subcarrier reuse/sharign within individual ISs is allowed that is discussed in Section 4.

4 Non-cooperative game

In this Section, we model (5)–(6) as a non-cooperative game in Subsection 4.1 and then solve the game in Subsection 4.2.

4.1 Game formulation

To optimise power allocation and subcarrier assignment vectors, we construct a non-cooperative game $\mathrm{NCG} = \{\mathcal{K}, \{X_i\}_{i \in \mathcal{K}}, \{u_i\}_{i \in \mathcal{K}}\}$, where $\mathcal{K}$ is the set of transmitting nodes and $X_i = \{x_{ij}^{n,q}\}$ is the strategy profile of node i. In accordance with the objective function (5) in the

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resource allocation problem and following the derived disjoint subcarrier sets in Fig. 3 Algorithm 2, the pay-off function of node i, u_i, is defined as

$$u_i(X_i) = \sum_{j\in o(i)} \sum_{n\in\Omega_{e_i}} \sum_{q=1}^{Q} q x_{ij}^{n,q} \tag{8}$$

where e_i is the index of IS containing node i. The strategy space of this game is represented by the Cartesian product of individual nodes' strategy profiles, that is, $\mathcal{S} = X_1 \times X_2 \cdots \times X_K$. Note that $X_{-i} = \mathcal{S}\backslash X_i$ denotes the set of strategy profiles for all nodes except for node i. The most common solution in game theory is NE, which is defined as follows.

Definition 2: A strategy profile $X^\star \in \mathcal{S}$ is a NE of NCG, if for all $i \in \mathcal{K}$

$$u_i(X_i^\star, X_{-i}^\star) \geq u_i(X_i, X_{-i}^\star) \quad \forall X_i \in \mathcal{S} \tag{9}$$

NE is the stable point of the game, where no one of the nodes can increase its own pay-off function by unilateral deviation. In other words, NE is a mutual best response from each node to the other nodes' strategies. In NCG, given X_{-t} as the strategy profile of node i's opponents and defined ISs, this node maximises its own pay-off function by solving problem

$$\max_{X_i} u_i \tag{10}$$

$$\text{s.t.} \sum_{j\in O(i)} \sum_{q=1}^{Q} x_{ij}^{n,q} \leq 1 \quad \forall n \in \Omega_{e_i} \tag{11a}$$

$$\sum_{n\in\Omega_{e_i}} p_i^n \leq P \tag{11b}$$

where Ω_{e_i} is the set of subcarriers that can be assigned to the outgoing links of node i. Note that the second term in the left-hand side of the inequality (6a) has been eliminated in (11a). This is because of the fact that if $n \in \Omega_{e_i}$ then $\sum_{j\in I(i)} \sum_q^Q x_{ji}^{n,q} = 0$ in (6a).

Despite the elimination of subcarrier reuse among ISs, as discussed in Section 3, it is worth to note that subcarrier sharing within each IS is possible as a result of non-conflicting links in each IS. This is addressed by constraint (11b) in which p_i^n is a function of interference generated on subcarrier n by the other nodes in that IS. In an iterative game, where individual nodes transmit on subcarriers sequentially, interference $I_{ij}^n(p_{-i}^n)$ can be computed once other nodes within that IS determine their transmit power. Therefore with a given power from other nodes, $\{p_i^n\}$ is a function of X_i as in (3).

4.2 Game solution

To solve the game, we need to present how each node i optimises its own pay-off function in (10)–(11). Towards this, we form the Lagrangian function

$$L(X_i, \lambda_i) = u_i - \lambda_i \left(\sum_{n\in\Omega_{e_i}} p_i^n - P \right) \tag{12}$$

where λ_i is the Lagrange multiplier. Accordingly, dual function is obtained as

$$D(\lambda_i) = \sup_{X_i} L(X_i, \lambda_i) = \max_{X_i} \left(u_i - \lambda_i \sum_{n\in\Omega_{e_i}} p_i^n \right) + \lambda_i P \tag{13}$$

Evaluating dual function for a given λ_i, we obtain the optimisation problem as

$$\max_{X_i} u_i - \lambda_i \left(\sum_{n\in\Omega_{e_i}} p_i^n - P \right) \tag{14}$$

$$\text{s.t.}(11\text{a}) \tag{15a}$$

Substituting u_i and p_i^n by their equivalents in (8) and (3), we solve (14) and (15) by assigning subcarrier $n \in \Omega_{e_i}$ to link ij_n with modulation rate q_n as

$$(j_n, q_n) = \arg\max_{(j,q):n\in\Omega_{e_{ij}}} \left(q - \lambda_i I_{ij}^n(p_{-i}^n) T_q / G_{ij}^n \right) \tag{16}$$

In other words, $x_{ij}^{n,q} = 1$ if $(j, q) = (j_n, q_n)$, otherwise $x_{ij}^{n,q} = 0$. Accordingly, transmit power on subcarriers can be obtained in (3).

Moreover, the Lagrange multiplier is obtained in the dual domain by solving the dual problem

$$\min_{\lambda_i \geq 0} D(\lambda_i) \tag{17}$$

For a given $\{p_i^n\}$, the dual problem is solved by the subgardient method as

$$\lambda_i(t+1) = \left[\lambda_i(t) - \alpha \left(P - \sum_{n\in\Omega_{e_i}} p_i^n \right) \right]^+ \tag{18}$$

where $\left(P - \sum_{n\in\Omega_{e_i}} p_i^n \right)$ is the subgradient of the dual function with respect to λ_i and α is the step size that should be small enough to ensure the convergence [18].

A non-cooperative game solution is of importance if it attains a NE. In the aforementioned solution, a given node i obtains its best response with the respect of opponents strategies in the feasible region of (10)–(11). Owing to the binary variables in X_i, this region is non-convex. On the other hand, existing fixed point theorems such as Kakutani [19], which are used for the proof of NE existence, are based on the convexity of the best response feasible region. Consequently, the existence of NE in the discussed NCG can not be established based on these theorems. Alternatively, we investigate the existence of NE via simulations in Section 6. Obtained results show that the game does not converge to a NE. This fact motivates the author to propose a price-based approach in the next Section.

5 Price-based subcarrier sharing

To overcome the lack of NE in NCG, we propose a price-based approach for subcarrier sharing in this section. The key motivation in this approach is to design a power pricing scheme to manage the interference throughout the network and to achieve an efficient power allocation accordingly. The interference generated by node i on subcarrier n degrades the pay-off functions of other nodes within the corresponding IS. To model this degradation, we define $R_i^n = \sum_{k \neq i} \left| \left(\partial u_k^n / \partial p_i^n \right) \right|$ as the price of a unit allocated power to subcarrier n by node i, where u_k^n is the pay-off of node k on this subcarrier. Let subcarrier n be assigned to link kj at node k. Under the assumption of $u_k^n = log_2(1 + \gamma_{kj}^n)$, we obtain

$$\frac{\partial u_k^n}{\partial p_i^n} = \left(\frac{G_{kj}^n p_k^n}{\ln\ 2} \right) \left(\frac{-G_{ij}^n}{\sum_{l \in \mathcal{L}} G_{lj}^n p_l^n + \sigma_2} \right)$$

substituting γ_{kj}^n in (2). We mitigate the interference effect by modifying the pay-off function of each node to include the cost of transmit power on subcarriers. Consequently, each node i in the price-based approach solves the problem

$$\max_{X_i} u_i - \sum_{n \in \Omega_{e_i}} R_i^n p_i^n \tag{19}$$

$$\text{s.t.}(11) \tag{20a}$$

It is assumed that the nodes prefer not to transmit on a subcarrier whenever its pay-off value gets negative. Using the same method in Section 4.2, the solution is obtained by assigning subcarrier single $\in \Omega_{e_i}$ to link ij_n with modulation level q_n as

$$\left(j_n, q_n \right) = \underset{(j,q):n \in \Omega_{e_i}}{\arg\max} \left(q - (\lambda_i + R_i^n) I_{ij}^n (p_{-i}^n) T_q / G_{ij}^n \right) \tag{21}$$

Moreover, the Lagrangian multiplier λ_i is computed similar to NCG in (18). It is noteworthy that the price of power transmission on subcarrier n in (21) is $\lambda_i + R_i^n$, which has been increased by the term R_i^n in comparison with (16). Using the introduced term R_i^n, node i would be able to discriminate between different subcarriers for the aim of power allocation, rather than the same price λ_i for all subcarriers in (16).

Given the aforementioned solution, Fig. 4 Algorithm 3 presents the PBSS scheme. This algorithm initialises the transmit power such that all nodes transmit the same power on the subcarriers. At each iteration of the algorithm, chosen node i* is allowed to update its own strategy profile and the transmit power as well. The prices on subcarriers corresponding to this node are computed in Step 6. Given $\mathcal{S}(t-1)$, node i* solves (19) and (20) so as to obtain its own transmit power on the subcarriers in Step 7. In Step 8, the transmit power of the other nodes is set to the same in the previous iteration so as to update the strategy vector $\mathcal{S}(t)$. The average pay-off achieved by each node so far is derived using an exponential moving average in Step 9, where M is the number of iterations over which the utilities are averaged. The game continues upon the sum of the magnitudes of differential utilities in two successive iterations would be less than a small enough value ϵ.

Algorithm 3

1: set $t = 0$ and $\overline{u}_i(0) = 0$ for all i.

2: set $p_i^n(0) = \frac{P}{|\Omega_{e_i}|}$ for all i and $n \in \Omega_{e_i}$.

3: **while** $\sum_i |\overline{u}_i(t) - \overline{u}_i(t-1)| \leq \epsilon$ **do**

4: $t = t + 1$.

5: choose node i^* in a sequential order.

6: compute the price $R_{i^*}^n$ for all $n \in \Omega_{e_{i^*}}$.

7: given $P_i(t-1)$ for ll $i \neq i^*$, solve (12)–(12) to obtain $X_{i^*}(t)$ and $P_{i^*}(t)$.

8: $P_i(t) = P_i(t-1)$ for all $i \neq i^*$.

9: $\overline{u}_i(t) = (1 - \frac{1}{M}) \overline{u}_i(t-1) + \frac{1}{M} u_i(t)$ for all i.

10: **end while**

Fig. 4 *PBSS scheme*

6 Performance evaluation

In this section, we compare the performance of the proposed NCG and PBSS schemes in the downlink of OFDMA transmission. Since NCG does not attain a NE, we record the highest achieved sum-rate value during the game as its performance for comparison. There are 128 subcarriers occupying a one MHz frequency channel, which is assumed to be 6-tap Rayleigh fading with 0.9 µs RMS delay spread. The exponential power delay profile of link ij is $g_{ij} e^{(-(l-1))}$, where g_{ij} is the first path's average power gain and l is the path index. Single-sided power spectral density of noise is assumed to be unity. Numerical results are obtained for the following networks.

- **Cellular network:** we consider 4 transmission nodes, where each node has 4 outgoing links, that is, N = 4 and L = 16. In this single-hop network, there is not a node with both arriving and outgoing links. As a result, all the links construct one IS, that is, all subcarrier are shared among all the links.
- **Multihop relay network:** numerical results are also obtained for a typical multihop relay network shown in Fig. 5, including a BS that sets end-to-end connections with end-nodes via relay nodes (RNs). In this network, the arriving and outgoing links in nodes n_2, n_3, n_4, n_5 and n_6 conflict with each other. Using Fig. 2 Algorithm 1, two ISs are constructed: $\text{IS}_1 = \{l_1, l_2, l_3, l_8, l_9, l_{10}\}$ and $\text{IS}_2 = \{l_4, l_5, l_6, l_7\}$.

For each link ij in both cellular and relay networks, it is assumed that $g_{ij} = g_S$ if node i is the corresponding transmitter of node j, otherwise $g_{ij} = g_I$, where g_S and g_I are the signal and interference gains, respectively. We perform the simulation with $g_S = 0$ dB and $g_I = -3$ dB. For one realisation of the channel, the variation of the pay-off values of the four transmitting nodes in the cellular network

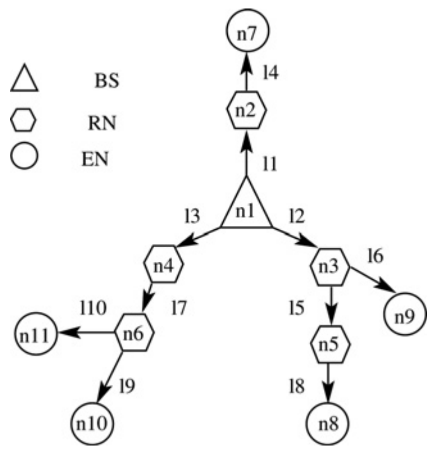

Fig. 5 *Relay network*

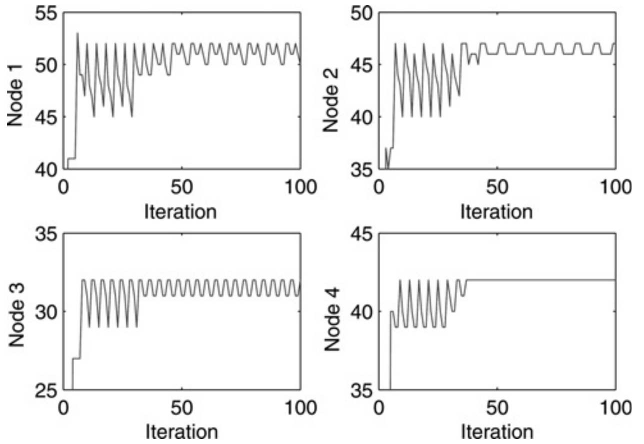

Fig. 6 *Pay-off variation in cellular network: NCG*

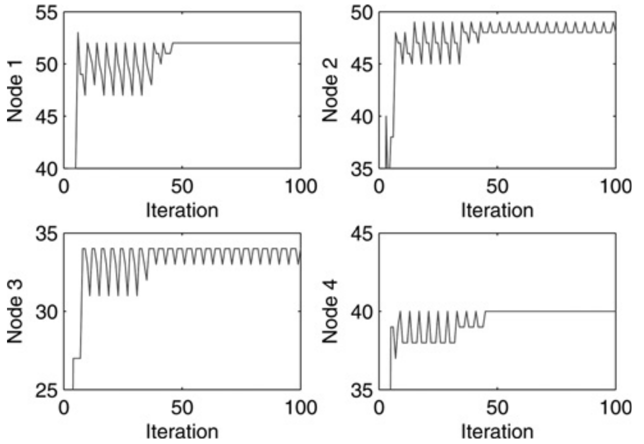

Fig. 7 *Pay-off variation in cellular network: PBSS*

for NCG and PBSS schemes are illustrated in Figs. 6 and 7, respectively. In both cases, some nodes pay-off values converge, whereas the others oscillate between some values in the steady state. This oscillation is because of the non-convex feasible region of (10)–(11), where the rate of a given subcarrier might vary over the time of simulation because of the change in the set of links to which the subcarrier has been assigned. In other words, there is subcarrier *back and forth* among the nodes of a given IS.

Moreover, the achieved sum-rate values of the cellular and relay networks with PBSS and NCG schemes are shown in Figs. 8 and 9, respectively. Despite of the oscillation in the individual nodes pay-off values, the sum-rate values converge in these figures. In other words, subcarrier back and forth among the nodes in the steady state does not alter the performance from the network viewpoint. In addition, PBSS outperforms NCG in both networks because of the imposed prices R_i^n on the transmit power.

In the following, we vary the interference to signal ratio, (g_I/g_S), and perform the simulations over 500 realisations of the frequency selective fading channel. We also obtain the sum-rate value from the scheduling scheme in our work [9], refered to as 'No sharing' scheme in this paper. In this scheme, subcarriers are not shared, that is, each subcarrier is used only once in the network. Achieved average sum-rate values are shown in Figs. 10 and 11 for the cellular and relay networks, respectively. As shown,

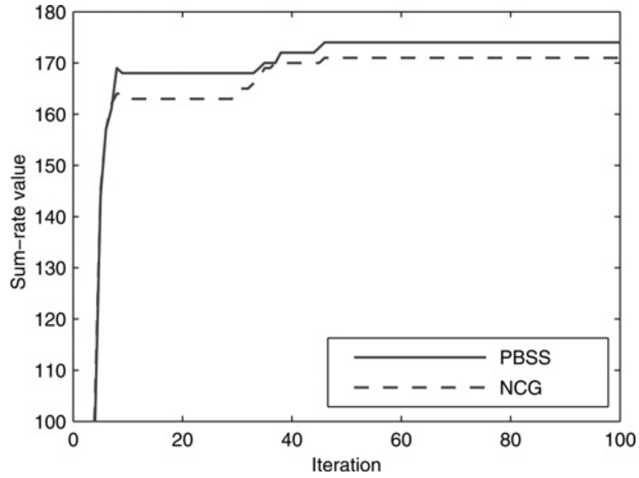

Fig. 8 *Sum-rate value in cellular network*

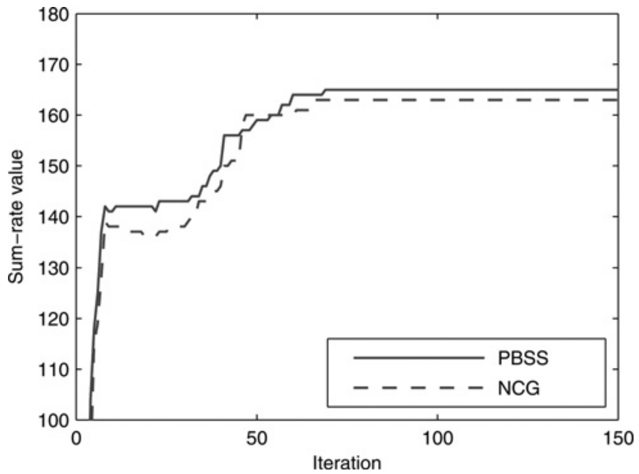

Fig. 9 *Sum-rate value in relay network*

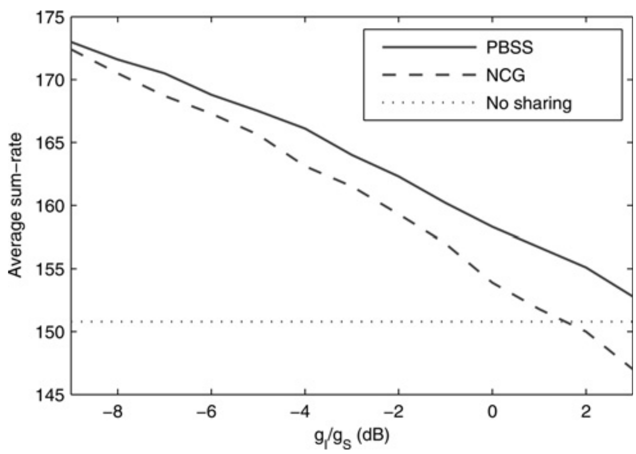

Fig. 10 *Average sum-rate value in cellular network*

subcarrier sharing generally outperforms the 'No sharing' scheme. In addition, the sum-rate value decreases as the interference increases in both PBSS and NCG schemes. This is because of the fact that co-channel interference resulted from subcarrier sharing degrades link capacities and sum-rates accordingly. On the other hand, 'No sharing' scheme does not suffer from co-channel interference

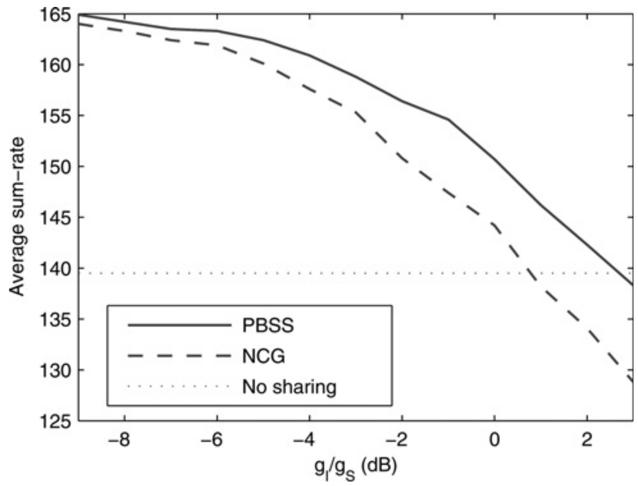

Fig. 11 *Average sum-rate value in relay network*

because of not subcarrier reuse. In both networks, PBSS outperforms NCG and their performance gap increases as the interference gain increases. This is because of the fact that every node in NCG transmits power on subcarriers selfishly. Therefore the degradation effect of this power on the other nodes grows with the increase of interference gain. On the other hand, the power prices on subcarriers imposed by the price-based approach prevents the nodes to increase their transmit power myopically. This issue results in an interference management scheme in the network. Because of this management, the performance of PBSS converges approximately to the same of 'No sharing' scheme when g_I becomes larger than g_S, whereas the performance of NCG is inferior to that of 'No sharing' scheme.

7 Conclusion

We have addressed the subcarrir sharing in OFDMA networks by a non-cooperative game and a game with power charging. While aggregate pay-off values are shown to converge, these games do not attain a NE. The possible explanation is because of subcarrier 'back and forth' among competitive nodes in the steady state. Moreover, power charging game outperforms non-cooperative game as a result of mitigating the co-channel interference. In overall, subcarrier sharing improves the network sum-rate value in comparison with no subcarrier sharing schemes, especially when the interference gain is low in the network.

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