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A Non-Cooperative Approach to the Joint Subcarrier and Power Allocation Problem in Multi-Service SC-FDMA Networks

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Abstract

In this paper a joint resource allocation problem is studied in a multi-service Single Carrier FDMA (SC-FDMA) wireless network. Mobile users request various services with different Quality of Service (QoS) characteristics and they determine in a distributed and non-cooperative manner a joint subcarrier and power allocation towards fulfilling their QoS prerequisites. Initially, a well-designed utility function is formulated to appropriately represent users' diverse QoS prerequisites with respect to their requested service. The subcarriers allocation problem is solved based on a multilateral bargaining model, where users are able to select different discount factors to enter the bargaining game, thus better expressing their different needs in system resources with respect to their requested service. The subcarriers mapping is realized based either on the localized SC-FDMA method where the subcarriers are sequentially allocated to the users or the distributed SC-FDMA via considering the maximum channel gain policy, where each subcarrier is allocated to the user with the maximum channel gain. Given the subcarriers assignment, an optimization problem with respect to users' uplink transmission power is formulated and solved, in order to determine the optimal power allocation per subcarrier assigned to each user. Finally, the performance of the proposed framework is evaluated via modeling and simulation and extensive numerical results are presented.

Keywords: Resource allocation; SC-FDMA; Service differentiation; Utility function; Multilateral bargaining; User-centric approach.

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1. Introduction

Demands for media rich wireless services have brought much attention to high speed broadband mobile wireless techniques in recent years. Single carrier frequency division multiple access (SC-FDMA), which utilizes single carrier modulation and frequency domain equalization, is the primary multiple access scheme for the uplink of the next generation wireless communication systems, where the total bandwidth is divided into orthogonal subcarriers in order to be allocated to multiple users [1].

Considerable research efforts have been devoted to the resource allocation problem in the uplink transmission of SC-FDMA wireless networks. Among the key elements that need to be considered and controlled in such environments are users' occupied subcarriers and their corresponding uplink transmission power. Given the inherent difficulty to jointly allocate a continuous resource, i.e. user's uplink transmission power, and a discrete resource, i.e. user's occupied subcarriers, to deal with this problem various heuristic subcarrier allocation methods have been proposed in the literature, while equal-bit-equal-power (EBEP) allocation and the water-filling method have been primarily adopted to allocate users' uplink transmission power [1].

Aiming at overall system's throughput optimization, a greedy algorithm has been proposed in [5], which determines the subcarrier with the highest channel gain among all available subcarriers and allocates it to the user

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who can maximize his marginal capacity with the allocated subcarrier. In [6] two subcarrier allocation algorithms have been proposed: a) the Matrix Algorithm (MA) and b) the Search-Tree Based Algorithm (STBA). In MA, a matrix is created containing the actual transmission rate for each user per each subcarrier. Then, the pair (user, subcarrier) with the highest actual transmission rate is determined and the specific subcarrier is allocated to the corresponding user. Considering the STBA, it creates a matrix containing also the achievable rate for each user at each subcarrier and at each iteration selects the two best pairs, i.e. (user, subcarrier). Then, for each pair deletes the corresponding row and column, till all elements are eliminated (i.e. the matrix becomes of size *1x1)*. Finally, the subcarrier allocation with the highest sum achievable rate is selected. All the above subcarrier allocation algorithms adopt EBEP allocation with respect to power, i.e. user's uplink maximum transmission power is equally distributed among user's occupied subcarriers [4].

On the other hand, aiming at considering users' specific Quality of Service (QoS) prerequisites, the authors in [7] present two heuristic subcarriers allocation algorithms, i.e. Low Complexity Delay Algorithm (LC-DA) and Proportional Fairness Delay Algorithm (PF-DA), considering delay and fairness constraints, respectively. LC-DA algorithm assigns each subcarrier to a user, if the constraints of maximum delay and minimum throughput are satisfied for all users, while considering the adjacency restriction for each users' allocated subcarriers. On the other hand, PF-DA algorithm adopts the proportion between the current throughput to the total throughput, instead of using the marginal utility, as in LC-DA algorithm, and it does not assign the subcarriers in order, but it gives higher priority to the users with the most critical delay requirement. In [8], the authors target at the maximization of users' sum-rate, where each user has a personal minimum rate constraint, which is imposed by his requested service. Specifically, they allocate the subcarriers to the users based on the maximum marginal weighted rate, while satisfying the adjacency restriction of the subcarriers and exploiting a linear estimate of the average number of subcarriers allocated to each user. In [9], an enhanced greedy subcarrier allocation algorithm is proposed, which in the first step allows N users with the higher priority to select first their initial subcarriers and then all users compete for the rest subcarriers, which are allocated based on the maximum marginal proportional fairness value. Also, the aforementioned subcarrier allocation policies adopt EBEP method, towards allocating users' uplink transmission power.

Finally, it should be noted that two different subcarrier mapping methods have been proposed in the literature for resource scheduling in SC-FDMA networks: localized (L-FDMA) and distributed (D-FDMA) [1], [2], [3]. In L-FDMA, the users occupy adjacent subcarriers, while in D-FDMA the users are assigned distributed subcarriers over the entire bandwidth. A special case of D-FDMA is the Interleaved FDMA (I-FDMA), where the occupied subcarriers by one user are equally spaced over the entire bandwidth. Both L-FDMA and D-FDMA have been adopted in the literature as subcarrier mapping methods [4] and will be subject of investigation in this paper.

1.1. Paper Contribution & Outline

In this paper, we propose a user-centric distributed non-cooperative subcarriers and users' uplink transmission power allocation, while supporting service differentiation. Towards allocating the subcarriers to the users, we adopt a multilateral bargaining model, i.e. Rubinstein's bargaining model, to obtain a feasible and stable subcarriers allocation, in terms of the number of subcarriers allocated per user [10]. The use of multilateral model of bargaining has been demonstrated as an efficient approach for energy-efficiency subcarrier allocation in SC-FDMA wireless networks supporting single service. The main novelty of this paper and key difference with respect to our previous work [11], is that users are allowed to select a preferable value of the discount factor to compete the rest of the users during the bargaining process, while in [11] all users were assumed to utilize the same factor, a fact that was not allowing the provisioning of service differentiation. The specific value of the discount factor reflects users' necessity to occupy subcarriers considering their requested service, via taking into account the differences in QoS prerequisites. Within the multilateral bargaining process, the game is sequentially played among users. Users that enter first the bargaining process are a priori favored compared to the rest of the users. Additionally, a user that adopts high value of the discount factor has also privilege compared to the rest of the users. Therefore, based on users' requested service appropriate value of the discount factor can be selected, so as to competitively request system's resources.

Each user adopts a general and realistic utility function, which represents user's service QoS-aware performance efficiency as a trade-off between the number of user's reliably transmitted bits and the corresponding consumed power (Section 2.1). The joint subcarriers and user's uplink transmission power allocation problem is formulated as a user-centric distributed non-cooperative optimization problem aiming at maximizing each user's overall utility (Section 2.2). The multilateral bargaining model with various values of users' discount factors is proposed towards allocating the subcarriers to the users while considering the specific QoS characteristics of users' requested services. Initially, an analytical example of the three-players bargaining game for subcarrier allocation is presented (Section 3.1) and then it is generalized and extended to the N-players subcarrier allocation (Section 3.2). After determining the number of subcarriers that should be allocated to each user via the multilateral bargaining game, two subcarrier mapping methods, i.e. L-FDMA and D-FDMA, are studied towards concluding which subcarrier should be allocated to each user (Section 4.1). In the localized subcarrier mapping method (L-FDMA) the subcarriers are allocated to a user in a consecutive manner, while in the distributed subcarrier mapping method (D-FDMA), the subcarriers are allocated to the users based on the maximum channel gain policy (i.e. a subcarrier is allocated to the user with the maximum channel gain).

Given the subcarriers allocation, a power control optimization problem is formulated and solved. Thus, user's optimal uplink transmission power per each occupied subcarrier is determined, instead of simply adopting the EBEP allocation or the waterfilling method to allocate users' uplink transmission power (Section 4.2). An iterative, distributed and low-complexity algorithm is proposed to converge to a stable subcarriers and uplink transmission power allocation (Section 5). Finally, the performance of the proposed approach is evaluated in detail and its operational characteristics are illustrated through analytical numerical results (Section 6.1). Additionally, an analytical evaluation is presented in terms of system's resources' usage when various services are requested by the users, as well as in terms of cell's capacity in number of users who have satisfied their QoS prerequisites (Section 6.2). Also, a comparison of L-FDMA and D-FDMA subcarrier mapping methods is presented considering power consumption and perceived satisfaction by the users (Section 6.3). Finally, Section 7 concludes the paper.

2. System Model & Background Information

The uplink of a single-cell SC-FDMA infrastructure wireless network, consisting of N continuously backlogged users is considered, where $\mathcal{N}$ denotes their corresponding set. The system bandwidth B Hz is orthogonally subdivided into N subcarriers, which set is $\mathbb{S}_{sub} = \{ s_i^j / i \in \mathcal{N} = \{1,2,...,i,...,N\}, j = 1,2,...,K_i \}$, where K_i denotes the number of subcarriers occupied by user i and $\mathbb{S} = \left\{ s_i^j / j = 1,2,...,K_i \right\}$ refers to the corresponding set. In the uplink of SC-FDMA wireless networks, there are some subcarrier allocation restrictions: a) exclusivity, i.e. only one user can occupy a single subcarrier and b) adjacency in L-FDMA, i.e. the user can occupy multiple subcarriers given that they are adjacent to each other.

Each user $i \in \mathcal{N}$ is characterized by a channel gain G_{i,s_i^j}, his uplink transmission power P_{i,s_i^j} for that subcarrier, its maximum value P_i^{Max}, which is imposed by the physical and technical limitations, and a corresponding signal-to-interference ratio (SIR) γ_{i,s_i^j}, which is given by:

$$\gamma_{i,s_i^j} = \frac{P_{i,s_i^j} G_{i,s_i^j}}{\sigma_{s_i^j}^2} \quad (1)$$

where $\sigma_{s_i^j}^2$ denotes the noise power of subcarrier s. Based on the above, the overall number of subcarriers in the system is $S = \sum_{i=1}^{N} K_i$ and for each user the inequality $\sum_{j=1}^{K_i} P_{i,s_i^j} \le P_i^{Max}$ should hold true.

2.1. Utility Function & Multiple Services

This paper aims at devising a user-centric and distributed joint subcarriers and users' uplink transmission power allocation in SC-FDMA wireless networks, via utilizing an N-person multilateral bargaining model with different users' adopted discount factors. Before presenting the formulation of the actual Multi-Service User-centric Distributed non-cooperative BArgaining model for Resource allocation problem (MUD-BAR problem) in Section 2.2, for completeness purposes in the following we present user's adopted utility function, as well as the corresponding QoS requirements imposed by the different type of services.

Aiming at aligning users' diverse and multiple QoS prerequisites under a common optimization framework, the concept of a well-designed utility function has been adopted, which represents users' satisfaction related to the allocated resources, i.e. subcarriers and uplink transmission power and correspondingly their QoS demands fulfilment. In wireless networks, a user ideally would prefer to transmit with low uplink transmission power P_{i,s_i^j} and achieve high throughput. Therefore, user's satisfaction at each of his occupied subcarrier $s_i^j \in \mathbb{S}_i \subseteq \mathbb{S}_{sub}$ can be expressed by the following utility function.

$$U_{i,s_i^j}(P_{i,s_i^j}) = \frac{R_{service} f\left(\gamma_{i,s_i^j}\right)}{P_{i,s_i^j}} \quad (2)$$

where $R_{service}$ is user's fixed designed transmission rate, depending on user's requested service and $f\left(\gamma_{i,s_i^j}\right)$ is his efficiency function representing the probability of a successful packet transmission for user i at subcarrier s_i^j. The efficiency function is an increasing and sigmoidal function of his SIR γ_{i,s_i^j} [11].

In next generation wireless networks, new applications and services, such as pervasive 3D multimedia, HDTV, VoIP, gaming, e-health, etc. are emerging, where each type of service imposes different QoS prerequisites. In this context, mobile users are expected to have different targeted throughput, thus requesting different amount of resources. Service differentiation can be achieved via assigning different numbers of subcarriers to different users, according to their demands and requirements. In a holistic and uniform way, users' various demands on system resources are captured and expressed in their overall utility function, which can be expressed as:

$$U_i(\boldsymbol{P_{i,s_i^j}} = \left[P_{i,s_i^1},...,P_{i,s_i^{K_i}}\right], K\ ) \ \sum_{j=1}^{K_i} U_{i,s_i^j}(P_{i,s_i^j}) \quad (3)$$

for user $i \in \mathcal{N}$, where K_i denotes the number of subcarriers allocated to user *i*. In general as it is observed in equation (3), different uplink transmission powers are adopted by each user to different subcarriers, when a user occupies multiple subcarriers. As it will be shown later via analytical numerical results, the proposed differentiation in users' uplink transmission power per subcarrier results in an energy-efficient resource allocation compared to the EBEP allocation, commonly adopted in the literature.

2.2. Multi-service User-centric Distributed non-cooperative BArgaining model for Resource allocation (MUD-BAR) Problem Formulation

The goal of each user is to maximize his utility via selecting an appropriate number of subcarriers K_i and a corresponding strategy of uplink transmission power P_{i,s_i^j} for each of his occupied subcarriers $s_i^j \in \mathbb{S}_i \subseteq \mathbb{S}_{sub}$. Therefore, the joint subcarrier and uplink transmission power allocation problem can be formulated as a maximization problem of each user's *i*, $i \in \mathcal{N}$ overall utility function.

$$\max_{\substack{P_{i,s_i^j}\in\mathcal{P}_i \\ 0<K_i\leq S}} U\left(\mathbf{P}_{i,s_i^j}\left[P_{i,s_i^1},\ldots,P_{i,s_i^{K_i}}\right],K_i\right)=\sum_{j=1}^{K_i}U_{i,s_i^j}\left(P_{i,s_i^j}\right)$$
$$\text{s.t.}\ \sum_{j=1}^{K_i}P_{i,s_i^j}\leq P_i^{Max},\ i\in\mathcal{N},\ S=\sum_{i=1}^{N}K_i \tag{4}$$

where $\mathcal{P}_i = [0, P^{Max}]$ denotes the set of user's $i \in \mathcal{N}$ feasible uplink transmission power, which is a compact and convex set with maximum and minimum constraints.

As it is analytically discussed in [12] solving a standard form of the optimization problem (4) is extremely complex due to the following reasons: (i) the extremely large search space that is created by the *N* users and the *S* subcarriers, and ii) the objective function in (4) is formulated as a complex form dependent both on a discrete (i.e. subcarriers) and a continuous (i.e. uplink transmission power) resource, while an additional power constraint for each user, i.e. $\mathcal{P}_i = [0, P^{Max}]$ should be considered. Thus, the straightforward solution of the optimization problem presented in (4) is clearly not practical and we need a different approach of treating this problem. Our proposed methodology involves reformulating the problem and solving it in a two-step approach. In the first step, the multilateral bargaining model is adopted towards determining subcarrier allocation. Each user is able to select a different value of the discount factor to enter the bargaining process, thus representing his priority and necessity to occupy a corresponding number of subcarriers considering his requested type of service. Then, in the second step, given the subcarrier allocation, an optimal power assignment to the allocated subcarriers is realized towards achieving energy-efficiency.

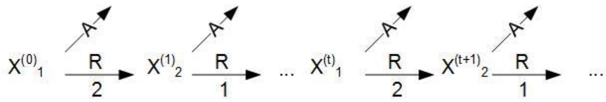

Fig. 1. Rubinstein's bargaining game

3 Multilateral Bargaining Model with Different Discount Factors towards Subcarriers Allocation

In SC-FDMA multi-service wireless networks, each user makes a resource request, in terms of number of subcarriers and uplink transmission power. In typical centralized systems, the base station is used to process users' requests, determine how many subcarriers should be allocated to each user, as well as his corresponding uplink transmission power and broadcast this allocation to the users. To eliminate typical problems associated with the centralized nature of such an approach [4], [5] in this paper a user-centric distributed non-cooperative subcarrier allocation algorithm is designed instead, in order to complete the subcarriers assignment to the users in a distributed manner. The solution to this problem may be found from the Rubinstein bargaining game [10].

Rubinstein proposed an infinite horizon bargaining model among two players towards dividing a cake of size *1* by making alternate offers and adopting common discount factor δ. Rubinstein's bargaining game can be summarized in the following graph. As it is observed in Fig. 1, $x_i(t)$ denotes the share vector that player *i* proposes in period *t*. If the proposal is accepted (A), the pie is shared accordingly. In the other case, if the proposal is rejected (R), the game goes to the next period and the other player makes a counteroffer. This bargaining model has been extended to *N*-players, where common discount factor δ is adopted by all players [13]. In this *N*-players infinite horizon game a unique partition is determined, as follows:

$$x_i = \frac{(1-\delta)\delta^{i-1}}{1-\delta^N} \tag{5}$$

where *i* is player's order in the bargaining game.

In this paper, the concept of bargaining game is extended towards allocating the subcarriers to the users, where users adopt different values of the discount factor to express their different needs of system resources with respect to their requested service. Next, a subcarrier allocation scheme based on game theory is presented. First, the three-player version of the subcarriers allocation game is given. Then, the subcarriers allocation scheme is extended to *N* players/users.

3.1. Three-players Subcarrier Allocation Game with different Discount Factors

The three-user sequential subcarriers allocation game belongs to the general category of bargaining games [13], where all the users must agree on how to share the total number of subcarriers. The fundamental concept of this game is that users must either accept the offer made by the other user, considering how the available subcarriers should be allocated, or reject it by making a counter offer in turns. An acceptance of an offer by all users ends the game, whereas a rejection by at least one user continues it. In [11] and based on equation (5), it has been shown that if the three users are discounted by a common factor δ, then the partitioning of the total number of subcarriers is given as:

$$\boldsymbol{K}^{*} = \left(\left\lfloor \frac{1-\delta}{1-\delta^{3}} S \right\rceil, \left\lfloor \frac{\delta(1-\delta)}{1-\delta^{3}} S \right\rceil, \left\lfloor \frac{\delta^{2}(1-\delta)}{1-\delta^{3}} S \right\rceil \right) \quad (6)$$

where $[\bullet]$ is the round process.

In the following, we examine the extension of *N*-players bargaining game, where different discount factors are adopted by each players. Let δ_1, δ_2, δ_3 denote the three users' different discount factors. For each user $i = \{1,2,3\}$ we define the bargaining operator Δ_i, as follows: $\delta_{ii} = 1$, $\delta_{jj} = \delta_j$, $\delta_{ij} = 1-\delta_j$, $\delta_{others} = 0$, where *i*: row and j: column. Thus, we have:

$$\Delta_1 = \begin{bmatrix} 1 & 1-\delta_2 & 1-\delta_3 \\ 0 & \delta_2 & 0 \\ 0 & 0 & \delta_3 \end{bmatrix}, \Delta_2 = \begin{bmatrix} \delta_1 & 0 & 0 \\ 1-\delta_1 & 1 & 1-\delta_3 \\ 0 & 0 & \delta_3 \end{bmatrix},$$

$$\Delta_3 = \begin{bmatrix} \delta_1 & 0 & 0 \\ 0 & \delta_2 & 0 \\ 1-\delta_1 & 1-\delta_2 & 1 \end{bmatrix}$$

Then, the overall bargaining operator $\Delta = \Delta_1 \Delta_2 \Delta_3$ of the trilateral game is calculated by: $\Delta = \prod_{i=1}^{3} \Delta_i$. The characteristic polynomial for Δ is determined as: $c(\lambda) = \det(\lambda I - \Delta)$ and its first order derivative $\left.\frac{\partial c(\lambda)}{\partial \lambda}\right|_{\lambda_{\max}=1}$ is evaluated at $\lambda_{\max} = 1$ (Perron – Frobenius theorem [10]). The overall bargaining operator Δ is partitioned accordingly, $\Delta = (\delta_{ij})_{3\times 3} = \begin{bmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{21} & \Delta_{22} \end{bmatrix}$, where Δ_{11} is a scalar and Δ_{22} is a square matrix of size *(3-1)*. We define the share function $sf(\delta_2, \delta_3) \equiv \det(I - \Delta_{22})$, which is independent of first user's discount factor δ_1 and we conclude to the unique efficient bargaining outcome $\boldsymbol{K}^{*} = \lfloor K_1^{*}, K_2^{*}, K_3^{*} \rfloor$, which is given by:

$$\boldsymbol{K}^{*} \begin{bmatrix} K_1^{*} \\ K_2^{*} \\ K_3^{*} \end{bmatrix} = \begin{bmatrix} \left\lfloor \frac{(1-\delta_2)(1-\delta_3)(1+\delta_3+\delta_2\delta_3)}{(1-\delta_1\delta_2\delta_3)^2 + \delta_1\delta_3(\delta_2-\delta_3) + \delta_1\delta_2(\delta_3-\delta_1) + \delta_2\delta_3(\delta_1-\delta_2)} S \right\rceil \\ \left\lfloor \frac{\delta_2(1-\delta_1)(1-\delta_3)(1+\delta_1+\delta_1\delta_3)}{(1-\delta_1\delta_2\delta_3)^2 + \delta_1\delta_3(\delta_2-\delta_3) + \delta_1\delta_2(\delta_3-\delta_1) + \delta_2\delta_3(\delta_1-\delta_2)} S \right\rceil \\ \left\lfloor \frac{\delta_3^{2}(1-\delta_1)(1-\delta_2)(1+\delta_2+\delta_1\delta_2)}{(1-\delta_1\delta_2\delta_3)^2 + \delta_1\delta_3(\delta_2-\delta_3) + \delta_1\delta_2(\delta_3-\delta_1) + \delta_2\delta_3(\delta_1-\delta_2)} S \right\rceil \end{bmatrix} \quad (7)$$

The above subcarrier allocation is the stable outcome of the three-players bargaining game and determines the number of subcarriers that should be allocated to each user. User's demand in system's resources, i.e. number of subcarriers, is appropriately represented by the value of the discount factor δ_i.

3.2. N-players Subcarrier Allocation Game

The *N*-players / users subcarrier allocation bargaining game is a generalization of the three-players / users case which was analytically presented above, with *N* users arranged in a fixed order, say *1, 2, 3,…,N*. The *N*-users subcarrier allocation based on multilateral bargaining model concludes to a partitioning of the total number of subcarriers. Let $0 \prec \delta_i \prec 1, \forall i \in N$ be the different value of the discount factor for each user. At time *0*, user *1* makes the first offer $\boldsymbol{K^0} = (K_1^0, \ldots, K_N^0)$. If all the other users accept the subcarrier allocation $\boldsymbol{K^0}$, then the bargaining game ends and the number of subcarriers that is occupied by each user is $K_i^0, \forall i \in N$. If at least one user $i \neq 1$ rejects $\boldsymbol{K^0}$, then the bargaining game continues at time *1* with an offer $\boldsymbol{K^1}$ by user *2*. If then the subcarriers allocation $\boldsymbol{K^1} = (K_1^1, \ldots, K_N^1)$ is unanimously accepted, the bargaining game ends. If this procedure is repeated in infinite horizon time of the bargaining game, it converges to the following subcarriers allocation:

$$K_i^{*} = \left\lfloor \frac{\delta_i^{i-1} sf_i(\delta_{\neq i})}{\left.\frac{\partial c(\lambda)}{\partial \lambda}\right|_{\lambda_{\max}=1}} S \right\rceil \quad (8)$$

The subcarriers' partition for each user $i \in \mathcal{N}$ is given by (8) via utilizing subscripts' rotation in the equation (8) for *i=1, 2, 3, …, N*. Furthermore given the number of subcarriers that are occupied by each user, a subcarrier mapping method is adopted (as it is analytically presented in Section 4.1) towards specifying the specific subcarrier's ID that is occupied by each user.

4 Subcarrier Mapping & Power Allocation

4.1. Subcarrier Mapping Methods

As it has been discussed in Section 1, two fundamental subcarrier mapping methods have been proposed in the literature, i.e. localized FDMA (L-FDMA) and distributed FDMA (D-FDMA). Given the specific number of subcarriers that is allocated to each user (determined in Section 3), the next step is to determine which subcarrier should be allocated to each user. In L-FDMA, the subcarriers scheduling process assigns adjacent subcarriers to each user. The main advantage of L-FDMA is that it achieves frequency selective diversity if it assigns each user to subcarriers in a portion of the entire bandwidth where that user has favourable transmission characteristics. On the other hand, in D-FDMA, subcarriers that are distributed over the entire bandwidth are assigned to the users, in order to avoid allocating many adjacent subcarriers in deep fading. By selecting users who are in favourable channel condition over the entire bandwidth, D-FDMA obtains multi-user diversity.

The criteria to select which subcarrier should be allocated to each user, either in L-FDMA or the D-FDMA are mainly maximum: a) channel gain [5], b) achievable uplink transmission rate [6] and c) marginal utility [7]. In this paper, we adopt both L-FDMA and D-FDMA and in Section 6.3 we present comparative results with reference to both approaches. More specifically, in L-FDMA, the users are assigned only sequential subcarriers to transmit. That is, *user 1* is sequentially assigned the first K_1^* subcarriers, *user 2* is assigned sequentially the next set of K_2^* subcarriers, etc. In the D-FDMA scenario, the subcarriers are allocated to the users based on the maximum channel gain policy.

4.2. Power Allocation towards Energy-Efficiency

Given the subcarriers allocation that is already performed and described in the previous section, each user has determined the number and IDs of his occupied subcarriers. Therefore, the goal of this section is to determine an optimal uplink transmission power allocation per each user's occupied subcarrier. Thus, we formulate a pure power control optimization problem considering each user's utility per each of his allocated subcarriers.

$$\max_{P_{i,s_i^{K_i^*}} \in \mathfrak{P}_i} U_{i,s_i^j}(P_{i,s_i^j}) \qquad \text{s.t.} \quad \sum_{j=1}^{K_i^*} P_{i,s_i^j} \le P_i^{Max} \tag{9}$$

In [11], it has already been proven that the power control optimization problem presented in (9) has a unique and stable solution in users' uplink transmission powers, which is given by

$$P_{i,s_i^j}^* = \min\left\{ \frac{\gamma_{i,s_i^j}^* \sigma_{s_i^j}}{G_{i,s_i^j}}, \left(P_i^{Max} - \sum_{\substack{u \neq j \\ u=1,\dots,K_i^*}} P_{i,s_i} \right) \right\} \tag{10}$$

Based on the above, a more efficient users' uplink transmission power allocation is achieved compared to the EBEP allocation or the waterfilling method, which a priori allocate users' maximum uplink transmission power [1].

5 MUD-BAR Algorithm

In this section, we present an iterative distributed and low-complexity algorithm, towards determining users' subcarrier and uplink transmission power allocation, following the methodology and outcomes described above. The first part allocates and assigns the subcarriers to all users, and the second part, given the subcarriers allocation and mapping, determines the optimal users' power allocation.

MUD-BAR Algorithm

Step 1: Subcarriers Allocation

At the beginning of time slot *t*, the subcarriers allocation $\boldsymbol{K}^* = \left(K_1^*, K^*, \dots, K_i^*, \dots, K^*\right)$ is determined via equation (8), based on the proposed multilateral bargaining model, where users adopt different values of discount factors, i.e. $\delta_1, \delta_2, \dots, \delta_N$, according to the QoS prerequisites that their requested service imposes.

Step 2 (a): L-FDMA Subcarriers Mapping

Given the subcarriers allocation in Step 1, users occupy sequential subcarriers. Thus, the user with number ID *1* occupies and transmits to the first K_1^* subcarriers, the user with number ID *2* occupies the following K_2^* subcarriers and so on till all users are exhausted.

Step 2 (b): D-FDMA Subcarriers Mapping

Given the subcarriers allocation in Step 1, users occupy subcarriers in a distributed manner based on the maximum channel gain policy, i.e. a subcarrier is allocated to the user that has the maximum channel gain G_{i,s_i^j} for the specific subcarrier.

Step 3: Optimal Uplink Transmission Power Allocation

Given the subcarriers allocation and the assignment to the users, each user *i*, $i \in \mathcal{N}$ computes his uplink transmission power based on equation (10) for each of his assigned subcarrier $s_i^j \in \mathbb{S}_i^*$. Set *k=0*.

Step 4: Set *k:=k+1*, delete the subcarrier *s* in the set of user's *i* available subcarriers, i.e. $K_i^{*(k+1)} = K_i^{*(k)} - \left\{s_i^j\right\}$, renew user's *i* maximum transmission power, i.e. $P_i^{Max(k+1)} = P^{Max(k)} \quad P_{i,s_i^j}^*$, and if $P_i^{Max(k+1)} \neq 0$ or $\mathbb{S}_i^* \neq \varnothing$ go to step 3, otherwise stop.

It should be noted that MUD-BAR algorithm refers to the used of closed forms (as developed before) to determine the subcarriers and uplink transmission power allocation, thus its complexity is low.

6 Numerical Results

6.1. Joint Subcarriers & Power Allocation

In this section, we provide some numerical results illustrating the operation and features of the proposed framework and the MUD-BAR algorithm. We assume that the total bandwidth *B* is divided into *S=256* subcarriers and *N=30* users reside within the cell. We assume two different types of service, i.e. type I and type II, where type I service is more demanding in terms of achievable throughput. Users are able to adopt different values of discount factor

$\delta_i \in (0,1]$ based on the type of service that they request and are placed in equal distance from the base station (i.e. d_i=*450m*) in order to have a common basis of comparison among them. We model users' path gains as $G_{i,s_i^j} = \Lambda_{i,s_i^j} / d_i^a$, where d_i is the distance of user *i* from the base station, *a* is the distance loss exponent, and Λ_{i,s_i^j} is a log-normal distributed random variable with standard deviation *8dB*, which represents the multi-path fading effect. Moreover, we set users' maximum uplink transmission power to $P_i^{Max} = 2$ *Watts* and $\sigma_{s_i^j}^2 = 5 \cdot 10^{-15}$. Users' efficiency function is given by: $f\left(\gamma_{i,s_i^j}\right) = \left(1-\exp\left(-\ _{i\ s_i^j}\right)\right)^M$, where *M=80*.

Fig. 2 illustrates the number of subcarriers allocated to each of the *N=30* users residing in the cell under three different scenarios: (i) common discount factor (δ*=0.9*), (ii) different discount factors among users based on the type of service that they request: (a) δ_I*=0.85*, δ_{II}*=0.95* and (b) δ_I*=0.89*, δ_{II}*=0.99*. Considering the first scenario, we observe that the first users inserted in the bargaining rounds are favored compared to the rest and a larger portion of the subcarriers is allocated to them. Thus, aiming at a more fair allocation among the users, a discount factor δ close to one would be more appropriate choice.

However, considering the two other scenarios, we observe that users' QoS prerequisites and their need to occupy a corresponding number of subcarriers based on the type of service they request, can be mapped to an appropriate selection of discount factor's value. More specifically, by observing the (ii-a) scenario, we conclude that the first *15* users are favored in terms of number of subcarriers due to the fact that they enter early the bargaining process, even if they have selected lower discount factor compared to the latter *15* users. On the other hand, the scenario (ii-b) clearly shows that users' privilege in occupying more subcarriers due to their early insertion to the bargaining process can be limited if they select a lower value of discount factor compared to the rest of the users. Thus, we conclude that the order of user's entry in the bargaining process, as well as the value of the discount factor, strongly affect the number of subcarriers that are allocated to each user. Therefore, the results demonstrated that a user who requests a demanding service in terms of throughput, e.g. type I service should enter early the bargaining process and/or adopt a high value of discount factor.

Fig. 3 and Fig. 4 illustrate the number of subcarriers and users' total uplink transmission power at the stable point of MUD-BAR algorithm, where each user adopts a different value for the discount factor, i.e. δ_{i+1}= δ_i*+0.007*, δ_1*=0.777*. Considering fairness in comparison, in the following results of this subsection, all the users request the same type of service (e.g. type II). The results reveal that the first users inserted in the bargaining process occupy a large number of subcarriers, even if they have low discount factor. Moreover, the latter users are also being allocated a large portion of subcarriers, due to the high value of their

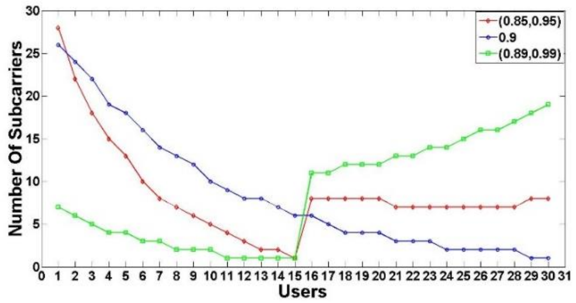

Fig. 2. Subcarriers allocation under 3 different scenarios: i) common δ*=0.9, ii-a)* δ_I*=0.85,* δ_{II}*=0.95 and ii-b)* δ_I*=0.89,* δ_{II}*=0.99.*

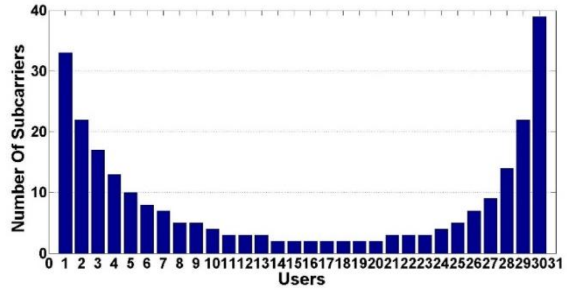

Fig. 3. Subcarriers allocation for increasing discount factor: δ_{i+1}= δ_i*+0.007*, δ_1*=0.777.*

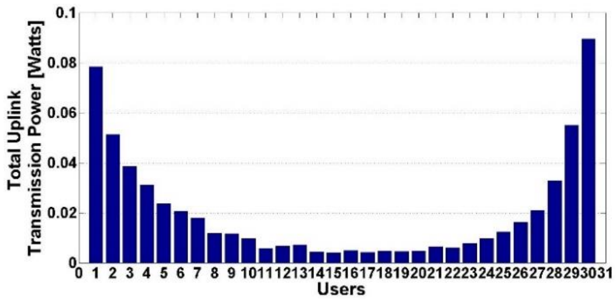

Fig. 4. Users' total uplink transmission power allocation for increasing discount factor: δ_{i+1}= δ_i*+0.007*, δ_1*=0.777.*

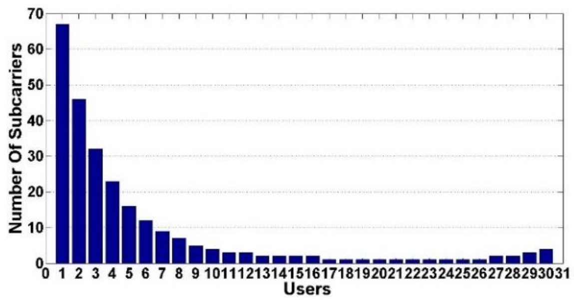

Fig. 5. Subcarriers allocation for increasing discount factor: δ_{i+1}= δ_i*+0.007*, δ_1*=0.700.*

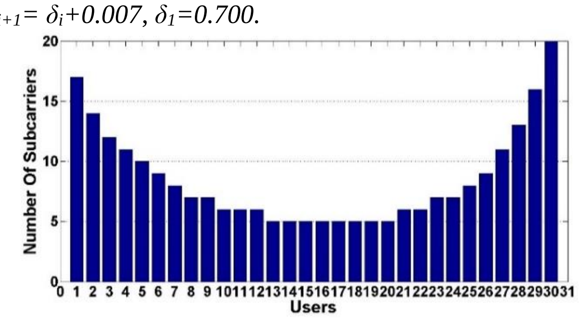

Fig. 6. Subcarriers allocation for smaller range of increasing discount factor: δ_{i+1}= δ_i*+0.003*, δ_1*=0.893.*

discount factor. Also, users' uplink transmission power follows the same trend as subcarriers allocation, due to the fact that the users who occupied more subcarriers, they transmit with higher total uplink transmission power. Furthermore, none of the users exhausts his maximum uplink transmission power, thus the proposed power allocation is more energy-efficient compared to the EBEP allocation and the waterfilling method, which allocate users' maximum power to their occupied subcarriers.

Fig. 5 illustrates subcarriers allocation to each of the $N=30$ users, while the initial value of the discount factor for the first user entered the bargaining process is set to $\delta_1=0.700$ and we keep the same step for the discount factors of the rest of the users, i.e. $\delta_{step}=0.007$. The results reveal that the latter users that entered the bargaining process do not have enough competitive value of their discount factor and they are also unfavored in terms of their order in the bargaining process, thus they obtain less subcarriers compared to the first users. This scenario could be applied in the case of the first users request a demanding service.

Finally, Fig. 6 presents subcarriers allocation to the users, while considering a smaller range of users' discount factors ($\delta_1=0.893$ and $\delta_{step}=0.003$). Based on the results, we observe that we obtain a more fair and balanced subcarriers allocation among users.

6.2. Service Differentiation & Cell's Capacity

A. Service Differentiation

The main goal of this subsection is to correlate users' requested type of service, the actual values of user's discount factor δ, user's order of entering the bargaining game and cell's capacity in terms of number of users who have satisfied their QoS prerequisites. As it was shown in the previous section, the users that enter earlier the bargaining and / or the users that have high value of discount factor are favored in terms of occupying greater portion of subcarriers. Thus, in the following we examine two different scenarios, i.e. best case and worst case scenario in terms of cell's capacity in number of users when service differentiation is considered. In the best case scenario (Fig. 7), the users who request more demanding service (e.g. type I) enter first the bargaining and / or have high value of the discount factor δ, while in the worst case scenario (Fig. 8) the opposite holds true.

The results reveal that in the best case scenario, the system can accommodate more users, while satisfying their QoS prerequisites. This observation holds true due to the fact that the users with higher resources' demands are favored in the best case scenario via either entering earlier the bargaining game and / or adopting a high value of discount factor. Thus, it is noted that user's order in the bargaining, as well as user's actual values of discount factor δ can be used by the optimization framework as the control parameters towards providing service priority to the users.

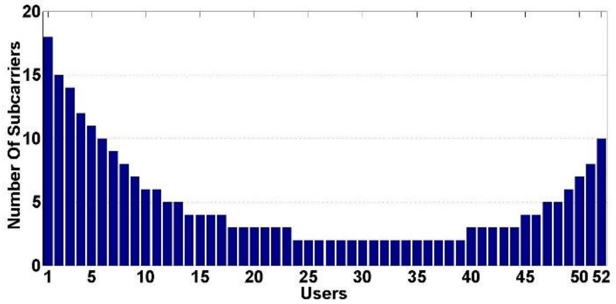

Fig. 7. Best case scenario: Subcarriers allocation considering service differentiation, i.e. voice-users' ID: 14-39, video-users' ID: 1-13 and 40-52, $\delta_{i+1}= \delta_i+0.0016$, $\delta_1=0.8984$.

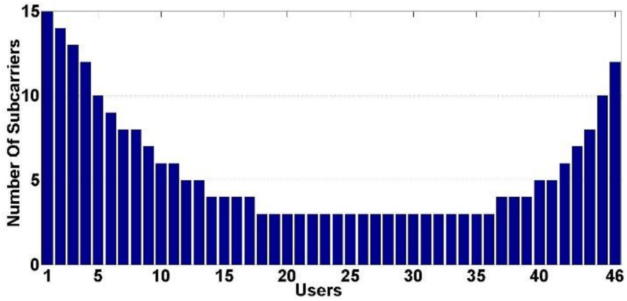

Fig. 8. Worst case scenario: Subcarriers allocation considering service differentiation, i.e. voice-users' ID: 1-13 and 36-46, video-users' ID: 14-35, $\delta_{i+1}= \delta_i+0.0019$, $\delta_1=0.8945$.

B. Cell's Capacity

In the following we present an analytical study illustrating the benefits of the proposed MUD-BAR algorithm in terms of satisfying the QoS prerequisites for an increasing number of users residing in the cell. Towards achieving fairness in the comparison we assume that all users request single service and are located at equal distance from the base station. Fig. 9 (a) – (c) present the subcarriers allocation versus the number of fully satisfied users for various ranges of the adopted values of discount factor δ by the users. The results reveal that as the range of the values of the discount factor δ approaches 1, the subcarriers allocation becomes fairer among users and correspondingly the system can serve more users in the single-service scenario. It is observed that the maximum capacity of the cell in terms of satisfied users is *58* users, where all users have fulfilled their QoS prerequisites. In the case of increasing more the starting point of the range of discount factor δ, it is noted that the users that enter the bargaining in an intermediate stage cannot fulfill their QoS prerequisites of the considered requested single service.

6.3. L-FDMA versus D-FDMA

In this section we present some comparative results among the two different subcarrier mapping methods proposed in the literature and considered in our study, i.e. localized FDMA (L-FDMA) and distributed FDMA (D-FDMA) [4] based on MUD-BAR algorithm.

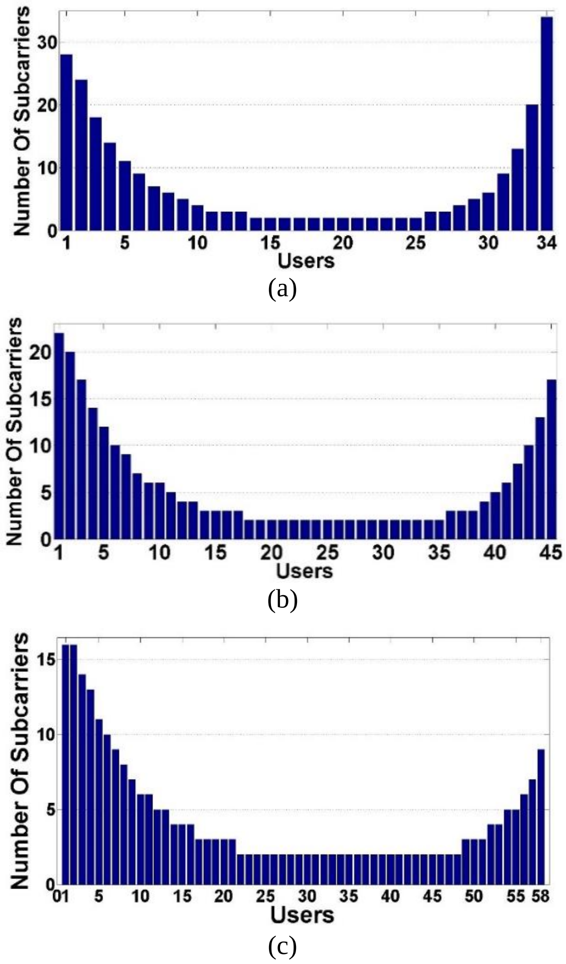

Fig. 9. Subcarriers allocation considering cell's capacity in terms of number of satisfied users for various ranges of the adopted values of discount factor δ by the users: (a) $\delta_{i+1}=\delta_i+0.006$, $\delta_1=0.782$, (b) $\delta_{i+1}=\delta_i+0.003$, $\delta_1=0.848$ and (c) $\delta_{i+1}=\delta_i+0.0015$, $\delta_1=0.8945$.

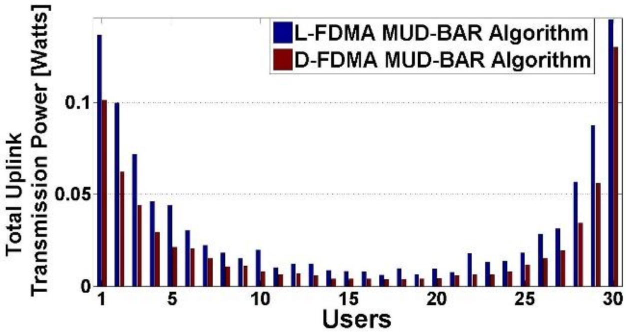

Fig. 10. Users' uplink transmission power considering L-FDMA and D-FDMA subcarrier mapping method in MUD-BAR algorithm ($\delta_{i+1}=\delta_i+0.007$, $\delta_1=0.75$).

Two different scenarios are presented: a) L-FDMA: the users occupy sequential subcarriers and b) D-FDMA: the users occupy subcarriers in a distributed manner based on the maximum channel gain policy.

Fig. 10 and Fig. 11 present users' uplink transmission power and achieved utility respectively for the two comparative scenarios at the stable point of the MUD-BAR algorithm, where each user ($N=30$) adopts a different value for the discount factor, i.e. $\delta_{i+1}=\delta_i+0.007$, $\delta_1=0.75$).

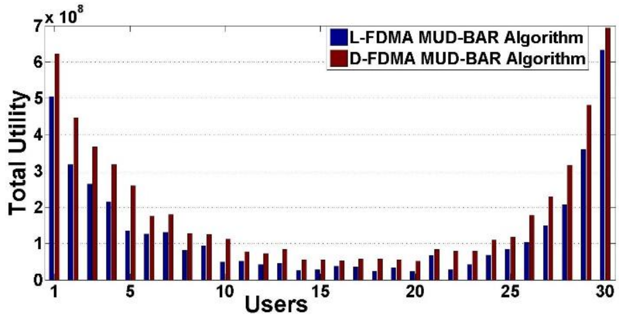

Fig. 11. Users' utility considering L-FDMA and D-FDMA subcarrier mapping method in MUD-BAR algorithm ($\delta_{i+1}=\delta_i+0.007$, $\delta_1=0.75$).

The simulation lasts *10000* time-slots towards providing average results. The results reveal that users' uplink transmission power is decreased (Fig. 10) in the D-FDMA scenario and their utility is increased (Fig. 11) due to the fact that each subcarrier is allocated to the user that presents the highest channel gain for the specific subcarrier. Thus, the maximum channel gain policy contributes to power saving and increases users' perceived satisfaction from the resource allocation process.

7 Concluding Remarks

In this paper, the problem of joint resource allocation in a multi-service Single Carrier FDMA wireless network is addressed. We introduced a user-centric distributed non-cooperative multilateral bargaining model for resource allocation in order to support service differentiation in multi-service wireless networks. The main novelty of the proposed framework is that the mobile users are able to select different discount factors to enter the multilateral bargaining process, thus better representing their needs in occupying system resources.

Following this initial subcarrier allocation, an optimal users' uplink transmission power allocation is proposed per each user's allocated subcarrier towards achieving an energy-efficient resource allocation. The proposed power allocation does not exhaust users' maximum uplink transmission power, compared to equal-bit-equal-power (EBEP) allocation and the waterfilling method, which have been widely utilized in the recent literature. Therefore the overall proposed framework presents an energy efficient joint resource allocation approach which can be used to provide service differentiation in SC-FDMA wireless networks. Furthermore, the operation of the proposed framework within either a localized subcarrier mapping method (L-FDMA) or a distributed subcarrier mapping method (D-FDMA) has been investigated and evaluated.

Based on the promising results of the proposed approach, part of our current and future work is to extend and apply the proposed framework in multi-service and multi-tier wireless networks, e.g. two-tier femtocell networks. In addition the proposed model can be examined in the context of the 5G wireless networks – specifically in M2M and D2D communication networks – where cellular users and machines / devices will be able to adopt different values of the discount factor, so as to express their priority in occupying a corresponding portion of resources.

Acknowledgements.
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References

[1] Rumney, M. (2008) 3GPP LTE: Introducing single-carrier FDMA. Agilent Technology, Tech. Rep..
[2] Myung, H. G. (2007) Introduction to Single Carrier FDMA. In *Proceeding of 15th European Signal Processing Conference (EUSIPCO)*, Sept. 2007.
[3] Rana, M. M., Kim, J. and Cho, W. K. (2010) Performance analysis of subcarrier mapping in LTE uplink systems. In *Proceeding of 9th International Conference on Optical Internet*, July 2010.
[4] Myung, H. G., Goodman and D. J. (2008) *Single Carrier FDMA: A New Air Interface for Long Term Evolution* (Wiley).
[5] Lim, J., Myung, H.G. and Goodman, D.J. (2006) Channel-Dependent Scheduling of Uplink Single Carrier FDMA Systems. In *Proceedings of IEEE 64th Vehicular Technology Conference (VTC Fall)*, September 2006.
[6] Calabrese, F. D., Michaelsen, P. H., Rosa, C., Anas, M., Castellanos, C. U., Villa, D. L., Pedersen, K. and Mogensen, P. (2008) Search-Tree Based Uplink Channel Aware Packet Scheduling for UTRAN LTE. In *Proceedings of IEEE 67th Vehicular Technology Conference (VTC Spring)*, May 2008, pp. 1949-1953.
[7] Delgado, O. and Jaumard, B. (2010) Scheduling and Resource Allocation in LTE Uplink with a Delay Requirement. In *Proceedings of 8th Annual Communication Networks and Services Research Conference (CNSR)*, May 2010, pp. 268-275.
[8] Marsch, P. and Fettweis, G. (2011) Uplink CoMP under a Constrained Backhaul and Imperfect Channel Knowledge. IEEE Transactions on Wireless Communications, vol. 10, no. 6, pp. 1730-1742.
[9] Zhang, M., Zhu, Y. (2013) An Enhanced Greedy Resource Allocation Algorithm for Localized SC-FDMA Systems. IEEE Communications Letters, vol.17, no.7, pp.1479-1482.
[10] Rubinstein, A. (1982) Perfect Equilibrium in a Bargaining Model. Econometrica, Econometric Society, vol. 50, no. 1, pp. 97-109.
[11] Tsiropoulou, E. E., Kapoukakis, A. and Papavassiliou, S. (2013) Energy-efficient Subcarrier Allocation in SC-FDMA Wireless Networks based on Multilateral Model of Bargaining. In *Proceedings of IFIP Networking 2013*, Brooklyn, 2013.
[12] Wong, I. C., Oteri, O. and McCoy, W. (2009) Optimal Resource Allocation in Uplink SC-FDMA Systems. IEEE Transactions on Wireless Communications, vol. 8, no. 5, pp. 2161-2165.
[13] Asheim, G. B. (1992) A unique solution to n-person sequential bargaining. Games and Economic Behavior, Elsevier, vol. 4, no. 2, pp. 169-181.