A Coalition Formation Game for Transmitter Cooperation in OFDMA Uplink Communications

Ali Chelli, Hamidou Tembine, and Mohamed-Slim Alouini

Abstract—The SC-FDMA (single-carrier frequency division multiple access) is the access scheme that has been adopted by 3GPP (3rd generation partnership project) for the LTE (long term evolution) uplink. The SC-FDMA is an attractive alternative to OFDMA (orthogonal frequency-division multiple access) especially on the uplink owing to its low peak-to-average power ratio. This fact increases the power efficiency and reduces the cost of the power amplifiers at the mobile terminals. The use of SC-FDMA on the uplink implies that for highly loaded cells the base station allocates a single subcarrier to each user. This results in the limitation of the achievable rate on the uplink. In this work, we propose a coalition game between mobile terminals that allows them to improve their performance by sharing their subcarriers without creating any interference to each other. The proposed scheme allows a fair use of the subcarriers and leads to a significant capacity gain for each user. The cooperation between the nodes is modelled using coalitional game theory. In this game, each coalition tries to maximize its utility in terms of rate. In the absence of cooperation cost, it can be shown that the grand coalition is sum-rate optimal and stable, i.e., the mobile terminals have no incentive to leave the grand coalition.

I. INTRODUCTION

Cellular communication systems have an inherent centralized topology where mobile terminals communicate with each other through a base station (BS). However, future mobile networks are expected to be decentralized, autonomous, flexible, and distributed [1]. In such networks, mobile terminals can communicate with each other which gives them the possibility to cooperate. This change in the technological landscape provides a wide range of opportunities and challenges.

Cooperation between users in the network allows to achieve several benefits, such as higher communication rate and enhancement in the error performance [2]. One of the major challenges faced when designing a cooperation scheme is the cost associated with cooperation. This cost is caused by the communication between nodes in a coalition for cooperation purposes. Additionally, if the cooperation scheme requires the intervention of a centralized intelligence, an extra amount of communication overhead is generated which yields an increase in the cooperation cost. This latter factor can limit significantly the cooperation gains and prevent the formation of the grand coalition. For this reason, the design of cooperation schemes that have a low cooperation cost is of primary importance.

Following this line of thought, we propose in this paper a transmitter cooperation scheme with negligible cost.

In next generation communication networks, a part of the network management is shifted from the BS to the mobile terminals [1], [3]–[6]. The fact that the decisions concerning power and resource allocation is not made in a centralized manner arises the need to study multi-agent distributed decisions. Game theory represents an adequate mathematical tool to address the interaction between various agents (the players) that can form a coalition in order to achieve a social optimum (maximum sum rate, minimum sum power consumption, etc). In this context, we address in this paper the problem of user cooperation for multiple access channel (MAC) from a game theoretic perspective.

In the literature, the problem of transmitter cooperation in MAC channels has been addressed in several research works. The authors of [3] presented a comprehensive survey of game models derived for the MAC channel, discussed their major findings, and outlined open research directions in this area. In [7], a multiple channel access game with competition is considered in multi-cell multi-user OFDMA (orthogonal frequency-division multiple access) networks. A noncooperative game model is introduced for rate adaptation, power control, and sub-channel assignment. In [7], if the Nash equilibria is not reached, a virtual referee modify the game rules by preventing some users from accessing some subchannels so that a better performance is attained. In [8], a coalition formation game among secondary BSs is investigated in a cognitive setting. The BSs cooperate together to improve their sensing capabilities. By doing so, they acquire a better knowledge regarding the free channels that can be used to serve their secondary nodes. A distributed algorithm is developed to find a Nash-stable set of coalitions. In [9], an auction game theoretic approach is utilized for resource allocation in OFDMA systems to achieve fairness. In this auction game, the Nash equilibria is reached using an iterative update algorithm based on bidding efficiency and the subgradient algorithm. A coalition formation game in TDMA (time division multiple access) system is proposed in [6]. There, transmitters cooperate together to create a virtual MIMO (multiple-input multiple-output) system. Under this setting, the nodes have to exchange their information packets at each transmission which increases considerably the cost of cooperation. As opposed to [6], our proposed scheme has a relatively low cost of cooperation and achieves similar rates.
compared with a virtual MIMO system. However, in our case the spatial diversity gain offered by the virtual MIMO system is substituted with a frequency diversity gain.

Using coalitional game theory, we propose in this paper a game between mobile terminals which cooperate in order to maximize their sum rate. The proposed game is suitable for uplink OFDMA systems. Users form a coalition and pull their efforts to increase their payoff. In order to limit the impact of selfish users on the formed coalition stability, we impose a rule dictating that each user can only use a single subcarrier at a time. This rule allows avoiding the peak to average power ratio (PAPR) problem on the uplink. Additionally, this rule permits to obtain analytical expressions for the individual user rate. We show that cooperation between mobile terminals leads to a significant improvement in the achieved individual rate for each user. This individual rate increases as the number of the users in the coalition increases. We derive expressions for the $\epsilon$-outage capacity\(^2\) for the case of the noncooperative scheme and the cooperative scheme. We also analyze the impact of the coalition size on the $\epsilon$-outage capacity. Moreover, we provide an expression for the gap between the individual rate and the ergodic capacity.

The rest of the paper is organized as follows. Section II describes the transmitter cooperation model, while Section III is devoted to the cooperation game properties. In Section IV and V, we investigate the outage capacity of the noncooperative and the cooperative schemes, respectively. The numerical results are presented and interpreted in Section VI. Finally, Section VII concludes the paper.

II. SYSTEM MODEL

We consider the scenario where mobile terminals are sending data on the uplink to a BS as illustrated in Fig. 1. We assume a Rayleigh block fading channel, where the channel gain remains constant during a whole time slot and varies independently for different time slots. The transmission rate is adjusted to the average SNR such that a fixed target outage probability $\epsilon$ is maintained. We assume that the BS assigns to each user a single carrier for uplink transmission. This situation occurs in the case of a highly loaded cell and thus the BS can only provide a single subcarrier to each user for uplink communication. This fact limits considerably the achievable rate for each user on the uplink.

Hence, rational users aiming to increase their rates would cooperate with each other to achieve this goal. Users form coalitions and pull their efforts to increase their payoff in terms of sum rate. Once a coalition is formed it can transmit on all subcarriers previously held by its users. A fundamental question in game theory is how to share the gain between coalition members such that no subset of users has an incentive to defect. If a subset of users within a coalition are communicating at a lower rate than the rate they can achieve by acting alone, these users will leave the coalition. In order to limit the occurrence of such event, we impose in the proposed game a fairness rule to improve the stability of the formed coalitions. The fairness rule imposes that a user cannot utilize two subcarriers simultaneously. On the other hand, if the transmitter uses more than a single frequency at a time this leads to a PAPR problem which degrades the quality of the communication and reduces the achievable rate.

The users within a coalition have to cooperate with each other to decide about the frequency hopping pattern that each of them will adopt. The final hopping patterns have to guarantee that none of the subcarriers is being utilized by two users at any instant. In this way, we ensure that no interference is occurring between users in a single cell. An example of a possible hopping pattern in a coalition of size 4 is illustrated in Fig. 2. For a coalition of size $M$, the subcarrier hopping pattern of each of the users can be obtained in a distributed manner by following these simple 3 steps: (i) each user in the coalition is assigned a number $m \in \{1, \ldots, M\}$, (ii) user 1 in the coalition chooses his subcarrier hopping pattern and send it to all the other users in the coalition (iii) user $m$ determines his subcarrier hopping pattern by performing $m$ circular shift operations on the hopping sequence received from user 1. These simple steps allow to obtain the subcarrier hopping pattern for all the users in the coalition in a distributed manner. Note as well that the amount of information exchange (which is also the only information exchange requested by the proposed cooperation scheme) for this algorithm is very small. This algorithm can be processed in parallel and distributed fashion which makes it scalable.

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\(^2\)Throughout this paper, the terms individual rate, $\epsilon$-outage capacity, capacity with outage, and transmission rate are used interchangeably.
achieved data rates by a given user are not impacted by the order in which he utilizes the different subcarriers and are only dependent on the number of subcarriers provided by the coalition [see (9), (10), and Fig. 4]. Hence, the use of static hopping pattern will not harm the performance (in terms of outage capacity) of the users in a coalition.

III. COOPERATION GAME PROPERTIES

To model the cooperation between transmitters in the proposed OFDMA uplink, we make use of coalitional game theory [10]. The transmitter cooperation scheme can be modeled as a coalitional non-transferable utility (NTU) game. Actually, the sum rate achieved by a coalition cannot be arbitrarily apportioned between the coalition members. This is as opposed to transferable utility games where the achieved payoff can be divided arbitrarily between the members of a coalition.

Definition 1. A coalitional game is defined by the pair \((N, V)\), where \(N\) is the set of the players, and \(V\) is a mapping that determines the payoffs that these players receive in the game. For a coalitional NTU game, the mapping \(V\) must satisfy that for every coalition \(S \subseteq N\), \(V(S)\) is a closed convex subset of \(\mathbb{R}^S\).

For the proposed game, the mapping \(V\) is defined as
\[
V(S) = \{x(S) \in \mathbb{R}^S | x_i(S) = R_i(S), \forall i \in S\},
\]
where \(R_i(S)\) represents the achievable rate by user \(i\) belonging to coalition \(S\). In (10), we provide an accurate approximation for this rate assuming that the size of the coalition \(S\) is equal to \(M\). The proposed game is an \((N, V)\) coalitional NTU game since the mapping \(V\) is a singleton set [see (1) and (10)], hence, closed and convex.

The proposed cooperation scheme entails little communication between users of the same coalition and can be considered almost cost free. This fact makes the cooperation always beneficial for the transmitters. To address such a cooperation game, traditional solution concepts for coalitional games such as the grand coalition exist as a solution concept if this game ensure that the core exists as a solution concept if this game ensure that the grand coalition (coalition of all players) will form. In the following, we provide a definition of the core for coalitional NTU games.

Definition 2. For a coalitional NTU game \((N, V)\), the core is defined as
\[
C_{NTU} = \{x \in V(N) | \forall S, \exists y \in V(S), \text{ such that } y_i > x_i, \forall i \in S\}.
\]

This definition for the NTU core implies that the grand coalition provides to each individual user a payoff allocation that is larger than any other sub-coalition \(S\). In this way, the core of NTU coalition games is stable since there exist no other coalition \(S\) that can provide a larger payoff than the grand coalition. Thus, no user has an incentive to leave the grand coalition. This fact guarantees the stability of the grand coalition.

For the proposed game, the absence of cost makes the utility of individuals in any coalition increase as the number of users in the coalition increases\(^3\). Due to this property, the grand coalition for this game is stable and the core is nonempty. Additionally, the fact that the individual payoff increases with the coalition size implies that the proposed game is also cohesive and superadditive [10], [11]. In order to converge to the grand coalition, we can use either an imitative learning algorithm [12] or a merge and split algorithm [13]. These algorithms are implemented in a distributed manner and allow to form coalitions among players dynamically which makes them well suited for wireless communication games.

IV. OUTAGE ANALYSIS OF THE NONCOORDERATIVE SCHEME

In the noncooperative scheme, the BS assigns a subcarrier to each user. Each mobile unit utilizes its resource without cooperating with other users. In our study, we consider a block fading channel. For such a channel, it is more appropriate to use the outage capacity as a performance metric rather than the capacity [14, p. 96].

In order to ensure that the outage probability does not exceed a threshold \(\epsilon\). The transmission rate \(R_i\) should not exceed the \(\epsilon\)-outage capacity \(C_\epsilon\). This latter is defined in [15] as the largest transmission rate \(R_i\) such that the information outage probability \(P_{out}(R_i) \leq \epsilon\). The \(\epsilon\)-outage capacity \(C_\epsilon\) can be obtained by solving the following equation
\[
P_{out}(C_\epsilon) = \mathbb{P}\{\log_2(1 + |h|^2\text{SNR}) \leq C_\epsilon\} = \epsilon
\]
\[
= \mathbb{P}\{|h|^2 \leq \frac{2^{C_\epsilon} - 1}{\text{SNR}}\}
\]
\[
= F_{\gamma}\left(\frac{2^{C_\epsilon} - 1}{\text{SNR}}\right),
\]
where \(\mathbb{P}\{\theta\}\) denotes the probability of the event \(\theta\). Under Rayleigh fading, the squared amplitude for the channel gain \(|h|^2 = \gamma\) is exponentially distributed and its cumulative distribution function (CDF) \(F_{\gamma}(x) = 1 - \exp(-\frac{x}{\gamma})\). It follows,
\[
P_{out}(C_\epsilon) = 1 - \exp\left(-\frac{2^{C_\epsilon} - 1}{\text{SNR}^\gamma}\right) = \epsilon.
\]
Consequently, the maximum achievable rate \(C_\epsilon\) can be expressed as
\[
C_\epsilon = \log_2\left(1 + \text{SNR}^\gamma \ln\left(\frac{1}{1 - \epsilon}\right)\right).
\]

It is worth mentioning that to achieve the rate \(C_\epsilon\) the transmitter needs to know only the channel statistics. Note as well that the rate \(C_\epsilon\) is very close to the instantaneous rate if a capacity achieving code is utilized by the mobile terminals. Actually, as stated in [16], for contemporary communication systems, such as 3G and 4G networks, a large number of symbols can be accommodated in one time slot.

\(^3\)Examining the expression of the capacity gap in (16) we can easily conclude that the rate achieved by any user increases as the size of the coalition \(M\) increases. The same fact can also be observed from Fig. 4.
A. The \( C \)-Outage Capacity

In the cooperative scheme, a coalition is composed of \( M \) terminals. We consider that each user has a single subcarrier. The users in the coalition share their resources in order to increase their achievable rate. In the proposed scheme, each user utilizes the \( M \) subcarriers belonging to a coalition according to a subcarrier hopping pattern. This latter is designed such that all the users of a coalition can transmit all the time without causing any interference to their partners in the coalition. An example of such hopping pattern is illustrated in Fig. 2.

To assess the performance of the proposed scheme, we use the capacity with outage as our performance metric. The \( \epsilon \)-outage capacity is defined as the largest transmission rate such that the information outage probability does not exceed a predefined value \( \epsilon \) [15]. For the proposed cooperative game, for each user in the coalition, the relationship between the information outage probability and the instantaneous rate is

\[
\epsilon = \Pr \left\{ \sum_{i=1}^{M} \log_2(1 + |h_i|^2 \text{SNR}) \leq M C^M_{\epsilon} \right\}
\]

(7)

where \( C^M_{\epsilon} \) is the CDF of the random variable \( \chi = \sum_{i=1}^{M} \log_2(1 + |h_i|^2 \text{SNR}) \).

The random variable \( \chi \) represents the accumulated mutual information (over \( M \) subcarriers) for a single user belonging to a coalition of cardinality \( M \). Note that the use of the normalization factor \( 1/M \) in (6) allows to evaluate the rate in symbol per channel use which makes the comparison between the rate of the cooperative and the noncooperative scheme fair. In (6), the term \( h_i \) denotes the channel gain of the link between the mobile terminal and the BS over subcarrier \( s_i \). Each user communicates with the BS using \( M \) different subcarriers \( \{s_1, \ldots, s_M\} \) according to a predefined hopping pattern. We assume for a given user that all the channel gains \( h_i(i = 1, \ldots, M) \) are independent identically distributed (i.i.d.). In particular, we consider that for all subcarriers \( |h_i|^2 = \gamma_i \) are exponentially distributed with the same mean power \( \bar{\gamma} \). This assumption is reasonable since the mean power associated with any subcarrier depends mainly on the distance \( d \) (the location of the mobile terminal relatively to the BS). Hence, users belonging to the same coalition and located at different distances from the BS would achieve different rates.

To determine the rate \( C^M_{\epsilon} \) in (7), we need to derive an expression of the CDF \( F_\chi(x) \). An approximate solution for the CDF \( F_\chi(x) \) can be derived as

\[
F_\chi(x) \approx \Gamma_{\alpha+1} \left( \frac{x}{\beta} \right)
\]

(8)

where \( \Gamma_{\alpha+1}(\cdot) \) is the incomplete gamma function [17, Eq.(6.5.1)]. The quantities \( \alpha \) and \( \beta \) can be determined as

\[
\alpha = \frac{\log \left( \frac{\beta}{\epsilon} \right)}{\log \left( 1 + \gamma_i \text{SNR} \right)} - 1 \quad \text{and} \quad \beta = \frac{\log \left( 1 + \gamma_i \text{SNR} \right)}{\log \left( \frac{\beta}{\epsilon} \right)}.
\]

(9)

Finally, we can approximate \( C^M_{\epsilon} \) as

\[
C^M_{\epsilon} \approx \frac{\beta}{M} \Gamma_{\alpha+1}^{-1}(\epsilon),
\]

(10)

where \( \Gamma_{\alpha+1}^{-1}(\cdot) \) denotes the inverse of the incomplete gamma function.

B. The \( \epsilon \)-Outage Capacity for Large Coalition Sizes

Let denote by \( \zeta_M \) the random variable given by

\[
\zeta_M = \frac{1}{M} \sum_{i=1}^{M} \log_2(1 + \gamma_i \text{SNR}).
\]

Note that \( \zeta_M \) represents the individual mutual information of a user belonging to a coalition of size \( M \). If \( M \rightarrow \infty \), invoking the strong law of large numbers, \( \zeta_M \) converges almost surely (with a probability 1) to the channel capacity. That is, as the number of the users in the coalition \( M \rightarrow \infty \) the individual rate of each user converges to the ergodic channel capacity \( \mu = \mathbb{E}\{\log_2(1 + \gamma_i \text{SNR})\} \), i.e.,

\[
\Pr \left\{ \lim_{M \rightarrow \infty} \zeta_M = \mu \right\} = 1.
\]

(11)

In the following, we investigate the case where we have a finite but large value of \( M \) and provide an approximate expression for the individual rate of each user under such conditions.

For the cooperative scheme, for a coalition of cardinality \( M \), the outage probability \( P_{out}^M(R) \) for a given user can be expressed as

\[
P_{out}^M(R) = \Pr \left\{ \frac{1}{M} \sum_{i=1}^{M} \log_2(1 + \gamma_i \text{SNR}) \leq R \right\}
\]

\[
= \Pr \{ \zeta_M \leq R \}
\]

\[
= \Pr \left\{ \sqrt{M} \left( \frac{\zeta_M - \mu}{\sigma} \right) \leq \sqrt{M} \left( \frac{R - \mu}{\sigma} \right) \right\},
\]

(12)

where \( \mu \) and \( \sigma^2 \) stand for the mean and the variance of \( \log_2(1 + \gamma_i \text{SNR}) \), respectively. Let denote by \( Z_M = \sqrt{M} \left( \frac{\zeta_M - \mu}{\sigma} \right) \). As \( M \) becomes sufficiently large and using the central limit theorem, the random variable \( Z_M \) converges in law to a Gaussian distribution with zero mean and unit
variance, i.e., $Z_M \sim \mathcal{N}(0, 1)$. It follows that for $M$ sufficiently large ($M$ can be finite or infinite), we can write

$$P_{\text{out}}^M(R) = \Pr\left\{ Z_M \leq \sqrt{M} \left( \frac{R - \mu}{\sigma} \right) \right\} \approx \int_{-\infty}^{\sqrt{M}(\frac{R - \mu}{\sigma})} \frac{1}{\sqrt{2\pi}} \exp\left( -\frac{x^2}{2} \right) dx = \Phi\left( \frac{\sqrt{M}(\mu - R)}{\sigma} \right),$$

(13)

where $Q(\cdot)$ stands for the tail probability of the standard normal distribution. In (a), we exploited the symmetry of the Gaussian distribution. We recall that the outage probability is equal to $\epsilon$, if we set the transmission rate to $C^M_e$, i.e., $P_{\text{out}}^M(C^M_e) = \epsilon$. On the other hand, using (13) and setting the rate $R$ to $C^M_e$ yields the following approximation

$$\epsilon = P_{\text{out}}^M(C^M_e) \approx Q\left( \frac{\sqrt{M}(\mu - C^M_e)}{\sigma} \right).$$

(14)

To capture the speed of the convergence of the rate $C^M_e$ to the ergodic capacity $\mu$, we introduce the quantity $\Delta_{\text{EC-OC}}$ as the difference between the ergodic capacity and the $\epsilon$-outage capacity, i.e., $\Delta_{\text{EC-OC}} = \mu - C^M_e$. Utilizing (14), we can approximate the rate $C^M_e$ and the ergodic capacity gap $\Delta_{\text{EC-OC}}$ as

$$C^M_e \approx \mu - \frac{\sigma}{\sqrt{M}} Q^{-1}(\epsilon)$$

(15)

$$\Delta_{\text{EC-OC}} = \mu - C^M_e \approx \frac{\sigma}{\sqrt{M}} Q^{-1}(\epsilon).$$

(16)

The approximation in (16) shows that the capacity gap $\Delta_{\text{EC-OC}}$ converges to zero approximately as fast as $O(1/\sqrt{M})$. Since the capacity gap $\Delta_{\text{EC-OC}} \to 0$ as $M \to \infty$, it follows that the $\epsilon$-outage capacity $C^M_e$ tends to the ergodic capacity $\mu$ as $M \to \infty$, i.e., $\lim_{M \to \infty} C^M_e = \mu$.

VI. NUMERICAL RESULTS

In this section, the analytical expressions presented in the previous sections are evaluated numerically and illustrated.

The expression of the $\epsilon$-outage capacity $C^M_e$ of an individual user belonging to a coalition of size $M$ is provided in (10). This result has been obtained based on the approximation of the CDF of the accumulated mutual information with the CDF of a gamma distribution. The accuracy of this approximation is essential to guarantee the correctness of the obtained expressions for the outage capacity. In Fig. 3, we depict the exact CDF of the accumulated mutual information evaluated by Monte Carlo simulations together with the CDF obtained through the gamma approximation (8). We can see from Fig. 3 that the gamma approximation is highly accurate. The presented results have been obtained for an SNR of 3 dB and for $M = 2, 4, 6$.

In Fig. 4, we depict the information outage capacity for the cooperative scheme and the noncooperative scheme. It can be observed from this figure that with a coalition composed of two users each individual user can communicate with a rate $C^M_e$ of 3.5 bps/Hz at an SNR=20 dB, while guaranteeing a fixed outage probability $\epsilon = 0.01$. Under the same conditions (SNR=20 dB and $\epsilon = 0.01$), for the noncooperative scheme a single user can only achieve a rate of 1 bps/Hz. Thus, by cooperating with just one user, each of the users in the coalition of size two can increase its rate by 350% on the uplink without any increase in its transmitted power and without any loss in terms of quality of service for each user (fixed outage probability $\epsilon = 0.01$). It is worth mentioning that the two users together are still using just two subcarriers. Hence, the achieved gain is also realized without the use of additional spectrum resources. For an SNR of 10 dB, a user can increase its transmission rate from 0.138 bps/Hz to 2 bps/Hz by forming a coalition with 9 other users ($M = 10$), which represents an improvement of the individual payoff of 1449% (the individual rate is multiplied by a factor of 14.49). The fact that the achieved rate for each user increases as the number of players in the coalition increases implies that the achieved sum rate of a given coalition increases as the size of the coalition increases. Consequently, the proposed coalition game is superadditive. A fair payoff division in terms of transmission rate is attained if the resources are shared according to the hopping pattern described illustrated in Fig. 2. A significant gain in individual rate is realized, if we increase $M$ from 1 to 2. However for larger values of $M$, adding a single player to a coalition yields a smaller gain. This gain decreases as $M$ increases. We can observe from Fig. 4 that the individual rate of the users get closer to the ergodic capacity of the channel as we increase $M$.

An expression for the gap $\Delta_{\text{EC-OC}}$ between the ergodic capacity and the rate $C^M_e$ is provided in (16). This ergodic capacity gap $\Delta_{\text{EC-OC}}$ is illustrated in Fig. 5. It can be seen from this figure that the gap $\Delta_{\text{EC-OC}}$ decays as $M$ increases. For a fixed value of $M$, the ergodic capacity gap increases as the SNR increases. For example, for the noncooperative scheme ($M = 1$), the ergodic capacity gap is 4 bps/Hz for
where the number of users tends to infinity, the achievable rate of the users in the coalition grows. At the asymptotic limits determined an expression for the gap between the achieved rate with cooperation and the noncooperative schemes. Additionally, we derived analytical expressions for the transmission rate for the cooperative scheme. In absence of cooperation cost, we propose that if the size of the coalition tends to infinity, the ergodic capacity gap ∆EC − OC of the channel.

In this paper, we proposed a coalition formation game for transmitter cooperation in uplink OFDMA communication. The proposed cooperation scheme has a very small cost and yields large gains in terms of transmission rate relatively to the noncooperative scheme. In absence of cooperation cost, we derived analytical expressions for the transmission rate for the cooperative and the noncooperative schemes. Additionally, we determined an expression for the gap between the achieved rate and the ergodic channel capacity. Our analysis revealed that the individual rate for a user in a coalition increases as the number of the users in the coalition grows. At the asymptotic limits where the number of users tends to infinity, the achievable rate tends to the ergodic capacity. By means of cooperation between transmitters in uplink OFDMA, the rate of individual users increases significantly. The gains in terms of achieved rate associated with cooperation can be exploited to reduce the transmitted power by the users in the coalition which yields a reduction in the network interference. This reduction in power consumption can be performed without any loss in terms of quality of service.

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