# Impact of Group Cooperation over Competitive Secondary Subnetworks

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## Abstract

*In this paper, we examine dynamic spectrum sharing between several networks of licensed and unlicensed users wherein the unlicensed user subnetworks compete against other unlicensed subnetworks for spectrum access while nodes belonging to the same subnetwork cooperate with each other. In such a hostile transmission environment, we observe that spectrum sharing schemes based on the assumption of strict user conformity will not perform as well relative to cooperative schemes in which the overall performance enhancement is achieved via the collective efforts of the nodes belonging to the same subnetwork. As an example case, a cooperation scheme based on opportunistic decode-and-forward is employed in this paper in order to demonstrate the effects of intra-group cooperation in an underlay spectrum sharing network and its impact on enhancing group performance. Moreover, the effect of intra-group cooperation on other unlicensed subnetworks operating within the same geographical and spectral vicinity is studied within the context of inter-group competition for spectrum access. Our results show that those secondary systems employing group cooperation can achieve a significant advantage over the secondary systems made of fully competitive selfish users in terms of successful spectrum coexistence.*

## 1 Introduction

With the rate at which wireless communication devices are becoming increasingly flexible in terms of their functionality, this has given rise to the introduction of new transmission paradigms and networking architectures that were not feasible only several years ago. One paradigm that has been receiving significant attention from the wireless community is *cooperation*, where wireless nodes assist in the transmission of information between source and destination nodes, where all the nodes belong to the same network. There are several approaches of implementing intra-group cooperation within the context of wireless networks, such as cooperative transmission [10, **?**], cooperative relay (CoopMAC [7]), dynamic spectrum leasing [5], and power control using utility functions with pricing [9]. Coalition game with cooperative transmission was used to help users located near network boundary in [4]. While cooperation in the form of resource sharing is the primary subject in the area of dynamic spectrum access (DSA), the major stream of research on cooperative communication focuses on sharing antennas to relay signals for others, hence exploiting diversity gain.

To the best of the authors' knowledge, all of the aforementioned approaches have focused on the direct performance benefit of the cooperating group itself resulting from diversity and/or relaying. However, it appears that none of the prior research activities have studied a heterogeneous network consisting of more than one group where users within a single group employs cooperative communications while other groups do not.

Furthermore, the case of coexistence between the primary users and more than one groups of secondary users has not been studied previously, regardless of whether or not cooperation was taken into consideration. The case of more than one groups of secondary users competing for limited network resources is becoming increasingly important in future networking environments as flexible network architectures such as ad hoc network and multi-hop network, enabled by advanced software-defined radio (SDR) and cognitive radio (CR) platforms, are more frequently becoming employed to fill the gap between spectrum allocation and user demands. The group architecture for secondary users has been proposed before, such as in the CORVUS system [2] that allows for opportunistic spectrum usage of secondary users while not interfering with primary users. Competition among secondary user groups was studied in a spectrum trading paradigm in [8]; however, each secondary user was assumed to make decisions independently and cooperation within a secondary user group was not incorporated in order to successfully facilitate winning inter-group competition.

Cooperative communication has been shown to be capable of extending transmission range [7] and combating fading [6]. While a user group can benefit directly from employing a cooperative scheme, there is also an impact on the other groups within the vicinity as well. An example is the issue of increased interference due to multiple nodes being involved within a cooperative scheme [11]. For conventional networks composed of only licensed users under fixed spectrum allocation, this may not be a significant issue. However, in a network based on a multiple access scheme consisting of both licensed and unlicensed transmissions operating in a concurrent manner, the impact of inter-group competition among unlicensed users can result in different outcomes when formulated within the context of a medium access game.

In this paper, we present an analysis and simulation results on the impact of cooperation within a subnetwork of unlicensed users on the competition among two subnetworks of unlicensed users competing for spectrum access. The major contributions of this paper are:

- Development of a system model for dynamic spectrum access comprising of two secondary networks with intra-group cooperation and inter-group competition;
- Implementation of intra-group cooperation using opportunistic decode-and-forward scheme; and
- Computation of the outage probabilities for users participating in spectrum access game with and without intra-group cooperation.

The rest of the paper is organized as follow. In Section II we describe the system model considered in this paper. Section III analyzes the outage performance for both the competing unlicensed user groups when none of them use cooperative transmission or one of them uses cooperative transmission. In Section IV, we present several simulated results illustrating the effects of using cooperative transmission on the outage performance of both user groups. We with several final observations and comments in the paper in Section V.

## 2 Proposed System Model

The system we are considering in this paper consists of two unlicensed user groups competing for underlay access to the spectrum owned by a collection of primary users, as depicted in Fig. 1. While conforming to the primary user interference limit, each of the two secondary user groups tries to enhance its own performance. Although Fig. 1 shows a centralized network structure for primary users and a mesh network structure for secondary users, the system can be generalized to include scenarios where both primary users and secondary users can adopt either centralized or mesh network structure.

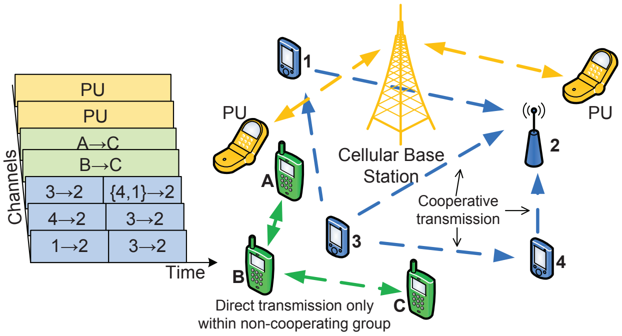

**Figure 1. System model of spectrum sharing among primary user and secondary user groups. In underlay spectrum sharing mode without perfect time synchronization, channels are defined by spreading "pseudo-noise" (PN) codes and there is multiple access interference (MAI) among channels. If a user group uses cooperative transmission, the potential relays will use the second time slot to forward the bits they received during the first times slot by means of amplify-and-forward (AF) or decode-and-forward (DF).**

We consider spectrum sharing be conducted via asynchronous multicode code division multiple access (MC-CDMA), which has been shown to be applicable to both centralized cellular networks and decentralized mesh networks [3]. Due to the nature of the competition between different secondary user groups, an overall power control and scheduling approach is difficult to achieve since the users in one group possess no interests in reducing interference to users belonging to the other group. In this case, we are considering intra-group cooperation in the form of relaying signals for other users in the same group using an opportunistic decode-and-forward (ODF) [1] described as follows: Before each transmission, the source calculates a desired spectral efficiency $R$, and broadcasts an ask-for-help message including destination information and spectral efficiency of $2R$. The broadcasted spectral efficiency is $2R$ instead of $R$ since the source will only be active during one of the two time slots if decode-and-forward is employed. Each potential relay that can successfully decode the message will respond to the source with an acknowledgement to the relay. If the source receives at least one response from the possible relays, it initiates a cooperative transmission mode via a decode-and-forward strategy possessing a spectral efficiency of $2R$. Otherwise, the direct transmission (DT) mode possessing a spectral efficiency of $R$ is employed. Each relay uses the same codebook and the same spreading code as the source uses to forward the message.

We assume that the primary system sets up an initial maximum output power limit on each unlicensed user, and sends additional messages to every secondary user via a broadcasting process across a common control channel in the event that the primary user is receiving too much interference. Since this power control procedure is aimed at controlling primary user interference instead of maintaining a baseline signal-to-interference-and-noise ratio (SINR) for each secondary user, algorithms that are relatively simpler to employ than CDMA-based cellular network power control schemes can be used to minimize the effort at the primary user base station. When the primary user interference limit is not exceeded, there is a primary user interference margin that the secondary users can fill in with their own signal power.

In this relay-based cooperative transmission scheme, transmissions are scheduled across two time slots. During the first time slot, the destination of a link (regardless of whether cooperative transmission is employed or not) receives:

$$y_{d(s)}(t_1) = \sum_{j\in\{\mathrm{S}\}} h_{j,d(s)}(t_1)c_j(t_1)\sqrt{P_j} + z_{d(s)}(t_1), \quad (1)$$

where $d(s)$ is the destination of source $s$, $\{\mathrm{S}\}$ is the set of active primary and secondary sources including $s$, the channel coefficient during $t_k$ between user $i$ and user $j$ is denoted by $h_{i,j}(t_k)$ which captures the effects of path loss, shadowing and fading, $c_i$ is the message of user $i$ multiplied with its spreading code, $P_i$ is the transmitting power of user $i$, and $z_{d(s)}(t_k)$ is the receiver noise during $t_k$.

In the second time slot $t_2$, each secondary user in either group receives both the copies of the messages from all relay groups $\Gamma(s)$'s in the cooperating group and signals from sources using direct transmissions in both groups:

$$\begin{aligned} y_{d(s)}(t_2) &= \sum_{i\in\{\mathrm{DF}\}} \sum_{r\in\Gamma(i)} h_{r,d(s)}(t_2)c_i(t_1)\sqrt{P'_r} + z_{d(s)}(t_2) \\ &\quad + \sum_{j\in\{\mathrm{S}\}\backslash\{\mathrm{DF}\}} h_{j,d(s)}(t_2)c_j(t_2)\sqrt{P_j}, \qquad (2) \end{aligned}$$

where $\{\mathrm{DF}\}$ contains the secondary sources that use relays, and $\Gamma(i)$ is the group of relays helping source $i$. $P'_i$ is the amount of power that user $i$ spends on each forwarded message. The sum of power that user $i$ spends on all simultaneously forwarded messages is equal the maximum output power limit $P_i$.

## 3 Proposed Performance Analysis

In this section, we derive the outage probabilities of a single secondary user with a desired spectral efficiency $R$ in both secondary groups when either both groups are using only direct transmission (DT) or one of the group is using opportunistic decode-and-forward (ODF). In order to have a fair comparison, both the primary user and secondary users are assumed to employ MC-CDMA across the same portion of spectrum with the same spreading gain denoted by $G$. Assuming Rayleigh fading, we model $h_{i,j}$ as complex Gaussian random variables with variance $\lambda_{i,j}$, such that $H_{i,j} = |h_{i,j}|^2$ is exponentially distributed with parameter $\lambda_{i,j}$. We also model $z_{d(s)}$ as zero-mean complex Gaussian variables with variance $N$.

### 3.1 Without Intra-group Cooperation

When neither of the unlicensed user groups employs cooperation, their outage probabilities for direct transmission can be expressed as:

$$\begin{aligned} \Pr[I_{\mathrm{DT}} < R] &= \Pr[I = \log_2(1+\mathrm{SNR}) < R] \\ &= \Pr\left[\frac{H_{i,d(i)}P_i}{N+J_i} < \frac{2^R-1}{G}\right], \qquad (3) \end{aligned}$$

where $I_{\mathrm{DT}}$ is the mutual information of direct transmission, $J_i$ is the interference received by secondary link $i$, and $R$ is the desired spectral efficiency in bps/Hz.

For simplicity, a simple power control scheme is employed in order to conform to the primary user interference constraint, such that all secondary users within the transmission range of the primary user base station use the same transmission power level, $P_i = P$ for any secondary user $i$, and the total interference received by the primary user base station is not above the interference limit, *i.e.* $\sum P_i H_{i,p} < I$. Let $K_p$ denote the set of primary users, $P_{p_i}$ denote the transmission power of primary user $p_i$, assuming that all $H_{i,j}$ values are independent and identically distributed with parameter $\lambda$, and assuming there are $k$ other transmissions in the vicinity. Thus, we have:

$$J_i = \sum_{p_i\in K_p} H_{p_i,i}P_{p_i} + \sum_{j=1}^{k} H_{j,i}P, \qquad (4)$$

where $H_{j,i}$ is an exponentially distributed random variable with parameter $\lambda$ and $\sum_{j=1}^{k} H_{j,i}$ possesses an Erlang distribution with parameter $\lambda$ and $k$. We assume that a power control scheme is employed by the primary user system in order to ensure that the minimal receiving SINR at the base station is satisfied for each user, hence $P_{p_i}$ is inversely proportional to the transmission gain $H_{p_i}$ between user $p_i$ and base station.

### 3.2 Cooperative Group Performance Analysis

If one of the two groups uses ODF, then the outage probability for the cooperating group, denoted later as group 1, is given as:

$$\begin{aligned}
&\Pr[I_{\text{ODF}} < R] \\
=\;& \Pr[I_{\text{DF}} < R] \Pr[\text{DF}] + \Pr[I_{\text{DT}} < R|\text{DT}] \Pr[\text{DT}] \\
=\;& \sum_{\Gamma(s)} \Pr[I_{\text{DF}} < R|\Gamma(s)] \Pr[\Gamma(s)] \\
&+ \Pr[I_{\text{DT}} < R|\text{DT}] \Pr[\text{DT}]. \qquad (5)
\end{aligned}$$

In the following, we present the derivations for the case when there is only one transmission in each user group for the sake of simplicity. Consequently, each relay uses its full power to forward the message from the source, *i.e.* $P_i' = P_i$ for any $i \in \Gamma(s)$.

In an asynchronous CDMA system (*e.g.* cellular system), when all primary users have distinct transmission power levels regulated by a fast closed-loop power control scheme, the mathematical derivation for the outage probability is intractable. Hence, we consider the scenario when there is no primary activity in the network. Although there is no primary user transmissions, the competing nature between two secondary user groups remains. The simulation results with primary user signals are given in Section 4.

The probability that a user in the group can serve as a relay for the source user is the probability that it can decode a message from source at the channel efficiency of $2R$, which is given as:

$$\begin{aligned}
&\Pr[r \in \Gamma(s)] \\
=\;& \Pr[I_{s,r} > 2R \mid \text{DT between } s, r] \\
=\;& \Pr\left[\frac{H_{s,r}P}{N + H_{I,r}P} > \frac{2^{2R}-1}{G}\right] \\
=\;& \int_0^\infty \lambda e^{-\lambda x} \cdot \exp\left[-\lambda \frac{(2^{2R}-1)(N+Px)}{PG}\right] dx \\
=\;& \frac{G}{G-1+2^{2R}} \cdot \exp\left[\frac{\lambda N(1-2^{2R})}{PG}\right], \qquad (6)
\end{aligned}$$

where $H_{I,r}$ is the sum of channel coefficients from the interferers, which in this case is the only source in the non-cooperative group.

$\Pr[\Gamma(s)]$, the probability that a group $\Gamma(s)$ of user can serve as relays for the source, is then given as:

$$\Pr[\Gamma(s)] = \prod_{r\in\Gamma(s)} \Pr[r \in \Gamma(s)] \cdot \prod_{r\notin\Gamma(s)} \Big(1 - \Pr[r \in \Gamma(s)]\Big). \quad (7)$$

The probability of using direct transmission, $\Pr[\text{DT}]$, is given as $\Pr[\text{DT}] = \Pr[\Gamma(s) = \emptyset]$. $\Pr[I_{\text{DF}} < R|\Gamma(s)]$ in Eq. (5), the outage probability for the source user when a group $\Gamma(s)$ of users serve as relays is given as:

$$\begin{aligned}
&\Pr[I_{\text{DF}} < R|\Gamma(s)] \\
=\;& \Pr\left[\frac{H_{s,d(s)}P + \sum_{r\in\Gamma(s)} H_{r,d(s)}P}{N + H_{I,d(s)}P} < \frac{2^{2R}-1}{G}\right] \\
=\;& \int_0^\infty \frac{\lambda^{|\Gamma(s)|+1} x^{|\Gamma(s)|}}{(|\Gamma(s)|)! e^{\lambda x}} \cdot \exp\left[-\frac{\frac{xPG}{2^{2R}-1} - N}{P\lambda^{-1}}\right] dx (8)
\end{aligned}$$

And we have the expressions for all terms in Eq. (5).

### 3.3 Performance of the Non-cooperating Group

The outage probability for the non-cooperating secondary user group, denoted as group 2, can be given as:

$$\begin{aligned}
&\Pr[I_2 < R] \\
=\;& \Pr\left[I_2 < R\middle|\text{DF}_{\text{Group1}}\right] \Pr\left[\text{DF}_{\text{Group1}}\right] \\
&+ \Pr\left[I_2 < R|\text{DT}_{\text{Group1}}\right] \Pr\left[\text{DT}_{\text{Group1}}\right] \\
=\;& \sum_{\Gamma_1(s_1)} \Pr\left[I_2 < R|\Gamma_1(s_1)\right] \Pr\left[\Gamma_1(s_1)\right] \\
&+ \Pr\left[I_2 < R|\text{DT}_{\text{Group1}}\right] \Pr\left[\text{DT}_{\text{Group1}}\right], \qquad (9)
\end{aligned}$$

where $I_2$ is the mutual information of users in group 2, the non-cooperating group, $\Pr[\text{DF}_{\text{Group1}}]$ is the probability that group 1 uses decode-and-forward, $\Gamma_1(s_1)$ is the group of relays for source $s_1$ in group 1, and $\Pr[\text{DT}_{\text{Group1}}]$ is the probability that group 1 uses direct transmission. The total probability is summed over the two situations where the users in group 1 can choose to use relays or not.

Users in group 2, the non-cooperating group, receive different amounts of interference in the two time slots. Since the source in group 2 sends independent pieces of information in the two time slots, we define the occurrence of outage as the event that outage happens in either one of the two time slots. Consequently, the outage probability of users in group 2 when users in group 1 are in the DT mode can be given as:

$$\Pr\left[I_2 < R\middle|\Gamma_1(s)\right] = \Pr\left[\min(I_{2,1}, I_{2,2}) < \frac{R}{2}\middle|\Gamma_1(s)\right], \quad (10)$$

where $I_{2,1}$ and $I_{2,2}$ are the mutual information for the source in group 2 in two time slots defined as:

$$I_{2,1} = \frac{1}{2}\log_2\left(1 + \frac{GH_{s_2,d(s_2)}P}{N + H_{s_1,d(s_2)}P}\right) \qquad (11)$$

$$I_{2,2} = \frac{1}{2}\log_2\left(1 + \frac{GH_{s_2,d(s_2)}P}{N + P\sum_{r_1\in\Gamma_1(s_1)} H_{r_1,d(s_2)}}\right) (12)$$

where $s_2$ is the source in group 2.

We observe from the above results that the cooperating secondary group tends to cause higher interference to other users when assuming fixed transmission power for every user, while benefit from multipath diversity. Such effects will be further illustrated with simulation results in the next section.

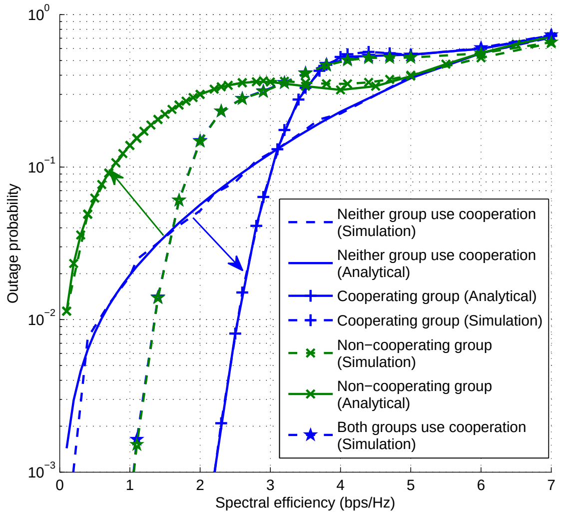

**Figure 2. Outage performance when neither group is using ODF, one group is using ODF, or both group are using ODF. The arrows show the deviation of outage probability when the cooperating group switches to ODF.**

## 4 Simulation Results

In order to show the effects of intra-group cooperation on inter-group competition of unlicensed users, we simulated a network scenario with a group of primary users and two groups of secondary users. We present results when the primary users are transmitting at an average of 1 W, 2 W, 4 W or are not transmitting. Each of the secondary users has an initial output power of 1 W. The primary user will broadcast warnings to the secondary users demanding a power reduction when its received interference is above a threshold. The modulation of both primary users and secondary users is assumed to be CDMA with a spreading gain of 50. We assume a Rayleigh fading channel among all users in the network and the channel coefficients are independent and identically distributed exponential random variables with parameter $\lambda = 1$. The primary users form a centralized network with nine mobile users that are constantly transmitting and one receiving base station. Each secondary group consists of 10 users, and the number of transmissions within a group follows Poisson distribution with parameter $\lambda_{\text{TX}}$. The cumulative amount of noise $N$ in the considered spectrum is 0.1 mW.

We first show in Fig. 2 the outage probability of the two groups when $\lambda_{\text{TX}} = 1$ in each group and there is no active primary transmission in the network. Both analytical results as derived in Section 3 and simulated results are shown in Fig. 2, which shows an acceptable match for both groups. As the cooperating group enjoys low outage probability at low expected spectral efficiency region, the other group that only uses direct transmission suffers a higher outage probability. Although in Fig. 2 we assumed that in the cooperating group every user that can decode the message from source will forward the message at full power, which means possibly more power consumption for each message, similar performance for both groups can be observed if the total power for each message remained the same as in direct transmission. This is due to the fact that in the second time slot of decode-and forward, the non-cooperating group will receive interference from all the relays in the cooperating group. When both groups use cooperation, their outage probabilities are indicated by the starred line in Fig. 2.

We define two crossing points of outage probability as follow:

$$\bar{R} = \arg\{P_{\text{out}}^{\text{ODF}}(R) = P_{\text{out}}^{\text{DT}}(R)\}, \quad (13)$$

$$\hat{R} = \arg\{P_{\text{out}}^{\text{ODF}}(R) = P_{\text{out}}^{\text{Non-coop}}(R)\}, \quad (14)$$

where $P_{\text{out}}^{\text{ODF}}(R)$ is the outage probability of using ODF, $P_{\text{out}}^{\text{DT}}(R)$ is of using direct transmission only, and $P_{\text{out}}^{\text{Non-coop}}(R)$ is of the non-cooperating group. The two crossing points indicate the value of spectral efficiency $R$ where the two outage probabilities are equal. In the region $(0, \bar{R}]$, a user will more likely to receive a lower outage probability by using ODF than using only direct transmission. In the region of $(\bar{R}, \hat{R}]$, although a user using ODF has greater chance to suffer higher outage probability than using only direct transmission, it will still enjoy lower outage probability than the other group that opts not to use ODF. Consequently, in the case where two group of unlicensed users compete for the access to a specific channel, which happens often in dynamic spectrum sharing networks, a user still has incentives to use ODF in the region $(\bar{R}, \hat{R}]$ so that the other user group would suffer higher outage probability and eventually quit the channel.

In Fig. 2, the outage performance of using ODF becomes worse than that with only direct transmission for rate beyond $\bar{R}$. This occurs since we assumed that potential relays have zero knowledge of channel conditions between the relays and the destination. Poor outage performance can be prevented if each potential relay stores a list of channel conditions between the relay and other users within communication range, and chooses to help forward a message only if it can support spectral efficiency of $2R$ as specified by the source.

Fig. 3 shows the results of having higher primary user signal power in the network, which causes higher outage probabilities for secondary users. The positions of both $\bar{R}$ and $\hat{R}$ are moved to lower values of spectral efficiency and higher values of outage probabilities as the primary user signal power increases. However, $\hat{R}$ is always greater than $\bar{R}$.

In the case when the primary user is not transmitting and there is only one group of secondary users in the network,

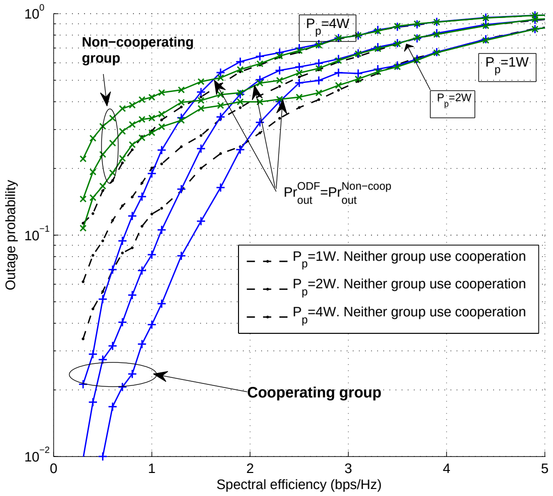

**Figure 3. Outage performance of the co-operating group using ODF and the non-cooperating group using direct transmission only under scenarios with different primary user transmission power.**

reducing the output power of each user by the same amount does not change the outage performance for every user as long as the noise level is significantly lower than the received signal. The utility of each user, if defined as the power efficiency of transmitting each bit, is therefore immediately increased due to less power consumption [9]. Such form of cooperation is sensitive to high interference. If there exists any user (no matter whether primary or secondary) that does not reduce its output power at the same time, the user group that reduces its power unilaterally will suffer an increase in outage probability and the gain obtained from a global power control scheme [9] no longer exists.

## 5 Conclusion

In this paper, we studied the spectrum sharing scenario where the spectrum is shared by a group of primary users and more than one group of secondary users. Such network formation has great potential in ad hoc wireless mesh networks with flexible spectrum access regulation. Secondary users form groups to compete with other secondary user groups for spectrum access regulated by the primary system in terms of maximum power and primary user interference limit. We analyzed the outage performance of competing secondary user groups and showed that using cooperative transmission within a user group can results in an increase in the outage probability seen by the competitor group and thus assist the survival of the user group itself.

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