Partner Selection in Cooperative Networks: Efficiency vs Fairness in Ricean Fading Channels

P. Castiglione*, S. Savazzi†, M. Nicoli†, G. Matz‡

*Telecommunication Research Center Vienna (FTW), Donau-City-Strasse 1, A-1220 Vienna, Austria
†Dip. di Elettronica e Informazione, Politecnico di Milano, P.zza L. da Vinci 32, I-20133 Milano, Italy
‡INTHFT, Vienna University of Technology, Gusshausstrasse 25/389, A-1040 Vienna, Austria
E-mail: castiglione@ftw.at, {savazzi, nicoli}@elet.polimi.it, gerald.matz@nt.tuwien.ac.at

***Abstract*— Enabling collaboration among users to relay messages for others is crucial to efficiently assign network resources and maximize network goodput. However, in some cases subsets of users would prefer a selfish behavior (by refusing cooperation) to protect their own performance. Depending on the application and on the particular propagation environment, an efficient grouping algorithm that assigns partners at MAC layer should conveniently address the problem of maximizing the network goodput without penalizing the performances of single users. This can be done by including specific constraints (user-fairness) that pose limitations on the amount of resources, e.g. energy, that might be reserved for relaying information of partners. In this paper the partner selection algorithms are designed to maximize the network lifetime while guaranteeing user-fair assignments. We analyze the network lifetime gain that can be achieved in a realistic network where fading significantly differs from Rayleigh and propose a novel low-complexity partner selection algorithm that maximizes the energy efficiency of the network while guaranteeing the given fairness constraint for each user.**

***Index Terms*— Cooperative diversity, amplify and forward, grouping algorithms, user-fairness, network lifetime.**

I. Introduction

Cooperative transmission techniques provide spatial redundancy, i.e. diversity gain, in networks of low-cost, typically single-antenna users [1], such as a wireless sensor or ad-hoc networks. Before cooperative transmission can start, the users shall choose the relay(s) to cooperate with. Partner selection is the most interesting and practical problem for medium access control (MAC) layer design [2], [3]. Typically, a central coordinator, e.g. the base station (BS), optimally assigns the partner(s) and allocates the transmission resources (time slots, transmit powers etc.) to each user. More specifically, in this paper battery-powered indoor users are allowed to engage in cooperative transmissions by amplifying and forwarding (AF) to the BS the signals received from the selected partners, as depicted in Fig. 1. The optimality criterion is the maximization of the network lifetime [4], [5]. The knowledge of the statistics of the fading

This work was supported by the European Project #IST- 216715 Network of Excellence in Wireless Communications (NEWCOM++), the Austria Science Fund (FWF) through grant NFN SISE (S10606 and S10607) and Ministero dell'Istruzione dell'Universita' e della Ricerca MIUR-FIRB Integrated System for Emergency (InSyEme) project under the grant RBIP063BPH. The Telecommunications Research Center Vienna (FTW) is supported by the Austrian Government and the City of Vienna within the competence center program COMET.

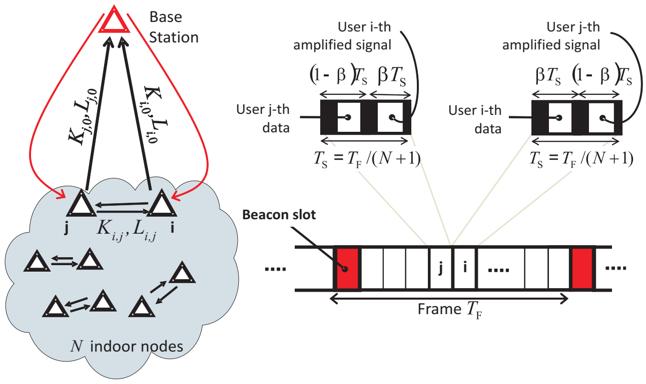

Fig. 1. Propagation setting (left). TDMA framing structure (right).

impairments, in addition to the path loss value, was shown to have a remarkable impact on the performance of partner selection in Ricean fading channels [5], in terms of energy consumption and on the degree of optimality of grouping algorithms. The additional information on the power of the coherent channel component provides an increase of the network lifetime by factors up to 100 (and even larger, depending on the propagation setting) compared to direct transmission.

Although enabling cooperation among users is crucial to maximize the lifetime of the network, a fraction of users might pay a significant price while serving as relays, since fairness and efficiency constraints cannot be satisfied simultaneously [6]. In principle, those users would benefit from a more selfish behavior, e.g. not to cooperate, to preserve their own performance with the drawback of penalizing the overall network lifetime (thus the lifetime of other potential partners). Depending on the particular application at hand and on the propagation environment, an efficient grouping algorithm should also address this trade-off by including user-fairness constraints that limit the amount of resources reserved for relaying.

In this paper a partner selection algorithm, tailored for Ricean fading channels, is proposed to allow collaboration as long as the energy required for data transmission of partner message is below a given (application-dependent) threshold. For realistic indoor-to-outdoor (I2O) uplink scenarios, we evaluate the degree of optimality of the proposed algorithm. Finally, we show that, depending on the strictness of the user-fairness constraint and on the network density, the algorithm exploits the knowledge of unbalanced fading statistics, i.e. *macro-diversity*, to improve the performance compared to multi-antenna systems (e.g. multiple-input-single-output, MISO).

II. System Model

The scenario under study consists of N battery-powered static users that are distributed indoors and communicate with a common BS located outdoors. The BS is acting as destination for all users (star network topology). As shown in Fig. 1, transmissions are organized into frames of duration T_{F}, subdivided into $N+1$ slots. A unique slot of duration $T_{\mathrm{S}} = T_{\mathrm{F}}/(N+1)$ is assigned to each user for time division multiple access (TDMA). One beacon slot is used by the BS to resynchronize the users and to configure the transmission policy.

Each wireless link between the i-th user $(i = 1,...,N)$ and the j-th user $(j = 0,...,N)$, with user $j = 0$ being the BS, is impaired by a base-band complex-valued fading channel $h_{i,j}$. The instantaneous signal-to-noise ratio (SNR) for a direct coherent transmission from user i to j is modeled as

$$\gamma_{i,j} = \left(\rho_i/\sigma^2\right)\left|h_{i,j}\right|^2, \tag{1}$$

where ρ_i is the transmit power for user i and σ^2 denotes the variance of the additive white Gaussian noise (AWGN). The fading power is arbitrarily distributed, $\left|h_{i,j}\right|^2 \sim f_{i,j}(x)$, with mean value $\mathbb{E}\left[\left|h_{i,j}\right|^2\right] = L_{i,j}^{-1}$.

Assuming block fading for the whole slot duration, the outage probability for user i communicating with user j is $\Pr\left[\gamma_{i,j} < \gamma_{\mathrm{th}}^{\mathrm{dir}}\right]$ with $\gamma_{\mathrm{th}}^{\mathrm{dir}} = \left(2^R - 1\right)/\mathscr{A}$, $0 < \mathscr{A} \leq 1$ modeling the modulation and coding format [7], while R refers to the spectral efficiency. Performance over fading channels can be approximated as [8]

$$\Pr[\gamma_{i,j} < \gamma_{\mathrm{th}}^{\mathrm{dir}}] \approx \left[\gamma_{\mathrm{th}}^{\mathrm{dir}}\sigma^2/\left(c_{i,j}\rho_i\right)\right]^{d_{i,j}}, \tag{2}$$

where $\approx$ indicates that equality holds asymptotically for high SNR, $d_{i,j}$ is the diversity order induced by fading, while $c_{i,j}$ is the coding gain.

III. Outage Analysis for AF Cooperative Transmission in Ricean Environments

AF relaying is chosen here due to its simplicity, compared to regenerative relaying, and practical implementation. Users periodically overhear the signals received from the partner and amplify and forward them towards the BS [1]. The BS is the centralized controller for specifying and communicating the cooperating partners, configuring the time-slot assignments and RF transmit powers. Partners are chosen based on the knowledge of the fading distribution as outlined in Sect. IV.

We assume that each user can cooperate with at most one partner. Let (i, j) be a pair of cooperating partners, each time slot assigned to any of these two users is further subdivided into two micro-slots. As shown in Fig. 1, for user i the first micro-slot spans a fraction $\beta_i = \beta$ of the available slot duration T_{S}. The first micro-slot is reserved for delivering the i-th user data. The second one with duration $(1-\beta)T_{\mathrm{S}}$ is reserved for transmitting the amplified version of the signal overheard from the partner j. Similarly, for user j the first micro-slot spans a fraction $\beta_j = 1-\beta$ for its own data and the remaining β to forward the partner i messages. The BS optimally combines the noisy replicas of the signal.

The outage probability is now evaluated for arbitrary fading by following the approach in [9]. Focusing on "variable gain AF" [10], the instantaneous SNR $\gamma_{(i,j),0}$ for user i transmitting on the micro-slot for a fraction β_i of the reserved slot and communicating to the BS with the help of partner j can be found as [10]:

$$\gamma_{(i,j),0} = \gamma_{i,0} + \left(\frac{1}{\gamma_{i,j}} + \frac{1}{\gamma_{j,0}} + \frac{1}{\gamma_{i,j}\gamma_{j,0}}\right)^{-1}. \tag{3}$$

The outage probability

$$\Pr[\gamma_{(i,j),0} < \gamma_{\mathrm{th};i,j}^{\mathrm{AF}}] \approx \frac{1}{2}\left(\frac{\gamma_{\mathrm{th};i,j}^{\mathrm{AF}}\sigma^2}{c_{(i,j),0}^{\mathrm{AF}}\rho_{(i,j)}}\right)^{d_{(i,j),0}^{\mathrm{AF}}} \tag{4}$$

is specified by parameters $d_{(i,j),0}^{\mathrm{AF}}$ and $c_{(i,j),0}^{\mathrm{AF}}$. These are the *effective* diversity and coding gains, provided by the AF "logical link" $(i, j), 0$, that depend on the fading distributions of the inter-user link and the uplink channel. The threshold SNR in (4) is $\gamma_{\mathrm{th};i,j}^{\mathrm{AF}} = \left(2^{R/\beta_i} - 1\right)/\mathscr{A}_c$, where the spectral efficiency R is increased[1] by multiplying with $1/\beta_i$. The term $\rho_{(i,j)}$ is function of the RF transmit power levels ρ_i and ρ_j. The outage probability for user j messages is similar to (4) with $\gamma_{\mathrm{th};j,i}^{\mathrm{AF}} = \left(2^{R/\beta_j} - 1\right)/\mathscr{A}_c$, power $\rho_{(j,i)}$, diversity and coding gain $d_{(j,i),0}^{\mathrm{AF}}$ and $c_{(j,i),0}^{\mathrm{AF}}$, respectively.

According to the experimental data analysis in [11], a Ricean fading channel with K-factor $K_{i,j}$ is assumed for the channel between users i and j (including the uplink channels for $j = 0$). Under this assumption, the outage probability for source i cooperating with partner j through AF relaying is given in (4), with $\rho_{(i,j)} = \sqrt{\rho_i\rho_j}$, $d_{(i,j),0}^{\mathrm{AF}} = 2$ and *effective* coding gain [9]

$$c_{(i,j),0}^{\mathrm{AF}} = \left[\frac{1}{c_{i,0}}\left(\frac{1}{c_{i,j}} + \frac{1}{c_{j,0}}\right)\right]^{-\frac{1}{2}}. \tag{5}$$

This parameter measures the power gain that would be available to user i in case partner j is chosen to amplify and forward its own signal. On the other hand, $c_{i,j} = \exp(K_{i,j})/\left[L_{i,j}(K_{i,j}+1)\right]$ denotes the coding gain for the separate link (i, j) and it is function of the K-factor $K_{i,j}$ (the measured power of deterministic channel component over the whole channel power) and the path loss $L_{i,j}$, measured over each link [9]. Notice that $c_{i,j} = L_{i,j}^{-1}$ in case of Rayleigh fading ($K_{i,j} = 0$).

IV. Partner Selection Strategy: Problem Formulation

The problem we tackle here is how to pair (or leave without partner) the users that are allowed to communicate to the outdoor BS. The aim is to minimize the maximum

[1]To guarantee the same efficiency as for the non-cooperative case.

energy consumed by the devices over the frame[2] with a constraint on the energy loss (or gain) for the single user. In our analysis, the energy consumption of the micro-processor, the amplifying circuitry during overhearing and the periodic resynchronization are assumed negligible and omitted. Without loss of generality, Gaussian modulation ($\mathscr{A} = \mathscr{A}_c = 1$) is assumed.

Energy consumption for single users. Approximating the outage probability by (2), the energy consumption for user i targeting an outage probability p must be, at least,

$$E_{i,0} \approx \frac{\gamma_{\text{th}}^{\text{dir}} \sigma^2}{c_{i,0}} \frac{T_S}{p}. \tag{6}$$

Energy consumption for cooperation with user-fairness constraint. The transmit energy for cooperating users is chosen such that the outage probability at the BS for both users is lower or equal to p. As a practical assumption, the RF transmit power level is kept constant over the reserved time slot[3]: this causes the cooperating partners to use the same transmit power [5]. The required overall energy consumption for user i cooperating with j to achieve the outage probability p is obtained from (4) as:

$$E_{(i,j),0}^{\text{AF}} \approx \frac{\gamma_{\text{th};i,j}^{\text{AF}} \sigma^2}{\min\left[c_{(i,j),0}^{\text{AF}}, c_{(j,i),0}^{\text{AF}}\right]} \frac{T_S}{(2p)^{1/d_{(i,j),0}^{\text{AF}}}}, \tag{7}$$

where the micro-slot fraction in $\gamma_{\text{th};i,j}^{\text{AF}}$ is set to $\beta_i = 1/2$ for the scenario at hand[4].

The energy gain $g_{i,j}$ achieved by user i cooperating with partner j, is defined as the ratio between the energy expenditure required by direct transmission and the energy consumption observed during cooperation. The gain $g_{i,j}$ is constrained to be above a threshold value $\overline{g}$ (*user-fairness*)

$$g_{i,j} = \frac{E_{i,0}}{E_{(i,j),0}^{\text{AF}}} \geq \overline{g}. \tag{8}$$

The threshold $\overline{g}$ can be interpreted as follows:

- for $\overline{g} < 1$, the user-fairness constraint prescribes a maximum amount of energy loss compared to the selfish or non-cooperative option that can be tolerated by the user i when cooperating with partner j;
- for $\overline{g} = 1$, the user-fairness constraint limits the cooperating user i to spend an energy that never exceeds the consumption that would be required for direct transmission;
- for $\overline{g} > 1$, the user-fairness constraint requires a minimum energy gain for user i as incentive to cooperate with j.

User-fairness is guaranteed to all cooperating users in the network. Thus, for any pair (i, j), it is $\min(g_{i,j}, g_{j,i}) \geq \overline{g}$.

[2]Minimizing this metric maximizes the network lifetime, assuming that battery capacity is the same for all the users.

[3]To avoid amplifier non-linearities.

[4]According to the I2O performance modeling described in [5], it is almost optimal to set $\beta_i = \beta_j = 1/2$ due to the fact that that $c_{i,j} \gg \max\left[c_{i,0}, c_{j,0}\right]$ is a likely condition in the considered I2O scenario.

Using (6), (7) and (8), the user energy gain can be formulated as the product of three terms

$$g_{i,j} = g_{\text{eff}}(R) \times g^{\mu\text{D}} \times g_{i,j}^{\text{MD}}. \tag{9}$$

Here, $g_{\text{eff}}(R) = \left(2^R - 1\right) / \left(2^{2R} - 1\right) < 1$ is the penalty factor paid for the rate increase from time slot splitting and $g^{\mu\text{D}} = (2p)^{1/d_{(i,j),0}^{\text{AF}}} / p = \sqrt{2/p} \geq 1$ is the gain, over small-scale fading (*micro-diversity* gain), that is obtained from the exploitation of redundancy from the partner link; finally, $g_{i,j}^{\text{MD}} = c_{(i,j),0}^{\text{AF}} / c_{i,0}$ accounts for the gain, over large-scale fading (*macro-diversity* gain), due to asymmetric links with different statistics, i.e. path losses and K-factors. Notice that, since $\lim_{c_{i,j} \to \infty} g_{i,j}^{\text{MD}} = \tilde{g}_{i,j}^{\text{MD}} = \sqrt{c_{j,0}/c_{i,0}}$, the largest minimum energy gain $\bar{g}$ that the system can guarantee is bounded as

$$\bar{g} < \bar{g}_{\max} = \lim_{c_{i,j} \to \infty} \left\{ \max_{c_{i,0}, c_{j,0},} \left[\min\left(g_{i,j}, g_{j,i}\right)\right] \right\} = g_{\text{eff}}(R) \times g^{\mu\text{D}}. \tag{10}$$

This upper bound is obtained for symmetric uplink channels[5], i.e. $c_{i,0} = c_{j,0}$. In other words, the system can guarantee the largest user-fairness only if no *macro-diversity* is available. Clearly, for threshold $\bar{g} \geq \bar{g}_{\max}$, cooperation shall not be allowed.

Energy gain for the MISO system with two transmit antennas. To exploit spatial redundancy, an alternative to AF cooperation is to deploy devices equipped with multiple antennas (MISO system). Assuming that multi-antenna devices system do not support relaying, then the user-fairness constraint is no longer applicable. In what follows, we compare the energy gain of the non-cooperative MISO system with the energy gain of the cooperative transmission for any degree of user-fairness (using single-antenna direct transmission as reference case). To allow a fair performance comparison with the case of pairwise cooperation, we consider the 2×1 MISO scenario where the users employ the Alamouti scheme. Assuming that the MISO links are independent-identically-distributed[6] (i.i.d.), it is intuitive that the energy gain g_{MISO} (with respect to single-antenna transmission) is only due to the *micro-diversity* gain with a penalty factor $1/2$ due to the power splitting between the two antennas

$$g_{\text{MISO}} = \frac{g^{\mu\text{D}}}{2}. \tag{11}$$

A. Optimal pairing for the min-max energy consumption with user-fairness constraint

Define the set of candidate pairing sets $\mathscr{P}$, such that one set $\xi \in \mathscr{P}$ contains up to $\lfloor N/2 \rfloor$ *disjoint* pairs of cooperative

[5]The more stringent condition $(L_{i,0}, K_{i,0}) = \left(L_{j,0}, K_{j,0}\right)$ is here not necessary since the coding gain is a sufficient statistic in the high SNR regime.

[6]The assumption of i.i.d. MISO links is of common use in the literature. Notice that the Alamouti scheme provides optimum performance with this assumption (2×1 MISO [12, Ch. 5]). However, this condition is generally not fulfilled in the considered fixed wireless access, where the coherent fading component results from the superposition of several reflected and diffracted fading contributions. Indeed, each antenna link can exhibit a different statistic. Assessing the optimal space-time code for this specific scenario in the finite SNR regime and comparing its performance goes beyond the scope of the present paper.

users: $\xi = \{(i,j),(k,h),...,(f,g)\}$. All the non-paired users belong to the set of single users $\mathscr{S}_\xi = \{q,s,\ldots,z\}$, such that $2|\xi| + |\mathscr{S}_\xi| = N$ (where $|\cdot|$ denotes the cardinality of the set). Given the candidate pairing set ξ and the corresponding single user set $\mathscr{S}_\xi$, the maximum energy consumed by a user in the network is $E^{\max}(\xi) = \max[\max_{(i,j)\in\xi} E^{\max}_{(i,j),0}, \max_{q\in\mathscr{S}_\xi} E_{q,0}]$, where $E^{\max}_{(i,j),0} = \max[E^{\mathrm{AF}}_{(i,j),0}, E^{\mathrm{AF}}_{(j,i),0}]$ is the maximum energy for the pair (i,j). The optimal pairing $\hat{\xi}$ is the solution to

$$\hat{\xi} = \arg\min_{\xi\in\mathscr{P}} E^{\max}(\xi) \quad (12)$$
$$\text{s.t. } g_{i,j} \geq \bar{g},\ \forall (i,j)\in\xi$$

The problem (12) can be formulated as a special case of the weighted matching problem on the non-bipartite graph $\mathscr{G} = (\mathscr{X},\mathscr{E})$ [13]. The set of vertices $\mathscr{X}$ corresponds to the set of users $\{1,\ldots,N\}$, which are fully connected by the set of undirected edges $\mathscr{E} = \{e_{i,j} : (i,j\in\mathscr{X})\ \&\ (i\leq j)\}$. The loops $e_{i,j=i}$ can be regarded as edges $e_{i,\bar{i}}$, where the virtual vertex $\bar{i}$ of the extended graph is connected only to i. The weights $w(e_{i,j<i}) = E^{\max}_{(i,j),0}$ and $w(e_{i,j=i}) = E_{i,0}$ are associated to all the edges and loops, respectively.

The optimal algorithm to solve this problem is referenced and adapted to our problem in [5]. Here, we need to handle the additional user-fairness constraint $g_{i,j} \geq \bar{g},\ \forall (i,j)\in\xi$. This problem can be solved by forcing $w(e_{i,j<i}) = \infty$, if $\min[g_{i,j}, g_{j,i}] < \bar{g}$ and thus by excluding all candidate pairing sets ξ that contain the pair (i,j).

B. Worst-Link-First Coding-Gain-based (WLF-CG) algorithm with user-fairness constraint

The optimal algorithm requires the BS to know all the inter-user coding gains for computing $c^{\mathrm{AF}}_{(i,j),0}$ for all the AF "logical links" from the pair (i,j) to the BS. To reduce the complexity, we propose to modify the worst-link-first algorithm (WLF-CG) described in [5]. The WLF-CG is shown to achieve better performance than a conventional worst-link-first algorithm based on second order statistics [3]. The algorithm is composed of two phases: a distributed phase where local information about the propagation environment is collected by the users and forwarded to the BS and a centralized one where the BS finalizes the pairing decisions.

In the distributed phase each user i communicates to the BS the set (list[7]) of candidate partners j for which $c_{i,j} > \tau \times c_{i,0}$, with threshold value $\tau \gg 1$ such that $c_{i,j} \gg c_{i,0}$.

In the centralized phase, the BS builds a sorted list of users from the smallest (worst-uplink) to the largest uplink coding gain (best-uplink). In order to meet the user-fairness requirement, the BS first removes from the list of user i the candidate partners j such that from (8) $g_{i,j} \simeq g_{\mathrm{eff}}(R) \times g^{\mu\mathrm{D}} \times \tilde{g}^{\mathrm{MD}}_{i,j} < \bar{g}$ or, equivalently, $c_{j,0} < \left[\frac{\bar{g}}{g_{\mathrm{eff}}(R)}\right]^2 \frac{c_{i,0}\cdot p}{2}$. At each iteration the BS assigns to the worst-uplink user i its best-uplink candidate partner j having i in his own list, and removes the paired users from the list. If no candidate partners satisfying the constraint are available for the worst-uplink user, the BS leaves the user without partner and removes it from the list. The algorithm is tailored for even numbers of users but can be adapted and evaluated for odd numbers as proposed in [5].

[7]The BS pairs only users i and j that are mutually in the lists of each other to satisfy the condition $c_{i,j} \gg \max[c_{i,0}, c_{j,0}]$. The condition allows the approximations $g^{\mathrm{MD}}_{i,j} \simeq \tilde{g}^{\mathrm{MD}}_{i,j}$ and $g^{\mathrm{MD}}_{j,i} \simeq \tilde{g}^{\mathrm{MD}}_{j,i}$.

V. Simulation Results

We evaluate the network lifetime performance of the partner selection algorithms in Sect. IV. The simulated network scenario is generated according to the stochastic model in [5, Sect. III]: N users are randomly distributed in a $25\mathrm{m}\times 25\mathrm{m}$ indoor environment and the BS is placed outdoors 50m away from the nearest wall. Path losses and K-factors $(L_{i,j}, K_{i,j})$ are log-normally distributed around a mean that is dependent on the link (i,j) distance. Performance results are averaged over 10^5 scenarios. The target outage probability is $p = 10^{-3}$ for all users with spectral efficiency $R = 1\,\mathrm{bps/Hz}$.

Fig. 2-a shows the network lifetime gain obtained by cooperation, averaged among the scenarios, with user-fairness constraint $\bar{g}$ varying form -80dB to $\bar{g}_{\max}(p,R) = 11.7$dB. The network lifetime gain is defined as $\mathbb{E}[E_{\max}(\xi = \oslash)]/\mathbb{E}[E_{\max}(\hat{\xi})]$, where $\xi = \oslash$ is the empty set and $\hat{\xi}$ is the pairing set selected by either the optimal (dash-dotted line) or the WLF-CG algorithm (solid line). In order to guarantee the required user-fairness $\bar{g}$, the threshold value τ in the WLF-CG algorithm is set to 20 dB (see Sect. IV-B). Optimal and suboptimal AF relay allocation are further compared to the non-cooperative MISO system. The shaded region highlights the cooperative network lifetime gain values that are below the energy gain $g_{\mathrm{MISO}} = 13.5$dB (equivalent to the network lifetime gain) provided by Alamouti transmission in a 2×1 MISO system with i.i.d. links. The trade-off between user-fairness and network lifetime is well described by Fig. 2-a. For less stringent user-fairness constraint values (below ~ -10dB), AF cooperation is at least as efficient as the MISO solution (for $N \geq 10$), achieving larger network lifetime gains where the user-fairness constraint becomes less severe. In the latter case, *macro-diversity* is on average extremely beneficial for the network lifetime and allows to outperform a system (MISO) based only on the exploitation of the *micro-diversity*. The performance (i.e. *macro-diversity*) can be further improved by increasing the density of the users. For $N = 50$, the WLF-CG algorithm (the optimal solution is not shown here) achieves remarkably better average network lifetime performance compared to the MISO case, even for user-fairness up to $\bar{g} = 0$dB. Nevertheless, the difference between the optimal and the WLF-CG pairing algorithms is high, e.g. ~ 6dB for $N = 10$, due to the conservative threshold τ in the WLF-CG algorithm. Notice that the case for $\bar{g} \to 0$ confirms the results in [5] only for the optimal solution, whereas the WLF-CG algorithm is penalized by the conservative choice of the threshold τ.

Fig. 2-b depicts the average percentage of cooperating users given a certain user-fairness constraint. The more severe the user-fairness constraint becomes ($\bar{g} \geq 0$dB), the less likely it is for the users to cooperate (especially for small

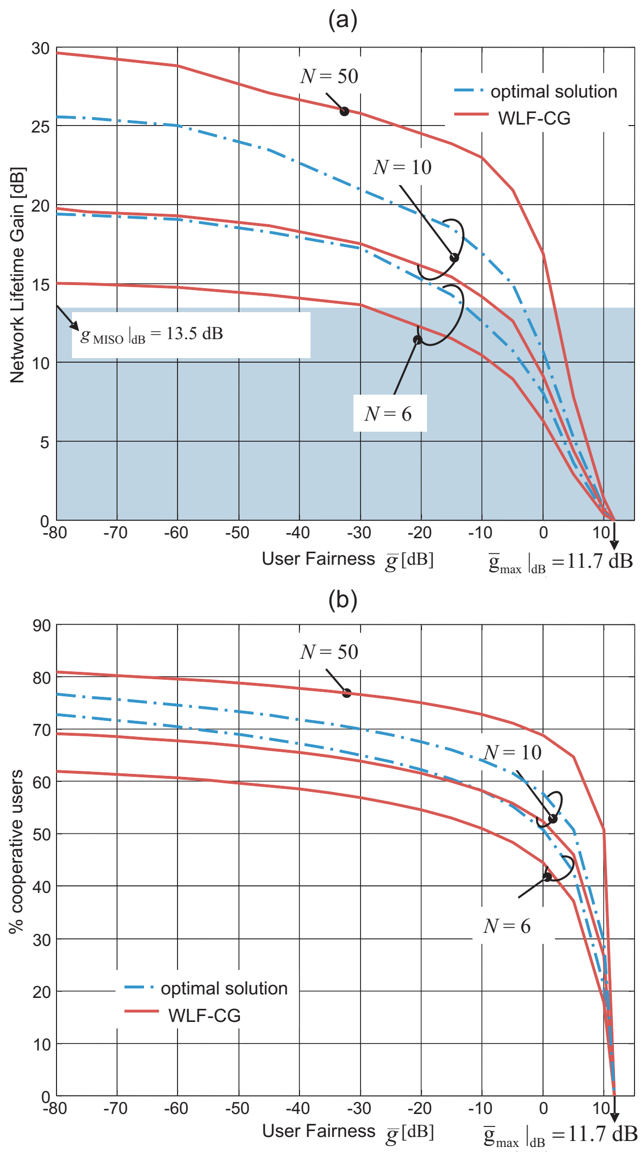

Fig. 2. (a) Average network lifetime (energy) gain vs. the user-fairness constraint. Outside the shaded region the proposed system performs better than Alamouti transmission in a 2×1 MISO system. (b) Average percentage of cooperative users vs. the user-fairness constraint.

N). More precisely, it is less likely that the worst-uplink user (that determines the network lifetime performance) is paired, thus, on average, the network lifetime performance are worse with respect to the MISO case. On the other hand, for less stringent constraints ($\bar{g} < 0$dB), the cooperative option becomes more attractive. This trade-off underlines the importance for an efficient multi-antenna resource allocation (whether cooperative or not) to carefully take into account the impact of *macro-diversity* in order to exploit it or, at least, to avoid possible detrimental effects.

VI. Concluding Remarks

In this paper we have investigated the network lifetime performance of AF cooperation with user-fairness constraints. User-fairness constraint is meant to limit the amount of energy reserved by one user for relaying the messages of any partner. The proposed user-fairness constrained network lifetime optimization problem has here a twofold interpretation: in the first one, cooperation is limited by a maximum amount of energy loss, compared to the non-cooperative option, that can be tolerated by the user ($\bar{g} < 0$dB); in the second one, a minimum energy gain for the user is introduced as incentive to cooperate ($\bar{g} \geq 0$dB). For the less stringent user-fairness requirements ($\bar{g} < 0$dB), we have proposed a low-complexity partner selection algorithm that obtains remarkable better performance gain over the non-cooperative Alamouti MISO transmission. The latter result is due to the benefits of the exploitation of the available *macro-diversity* (i.e., the distribution of the K-factor and path loss values in the multi-link Ricean fading channel). In a realistic I2O cooperative network with 50 static indoors users, our partner selection algorithm can achieve on average a network lifetime increase by factor 10 compared to the 2×1 MISO and 200 compared to single-antenna direct transmission, provided that the users can tolerate up to 10dB energy loss. On the other hand, for strict user-fairness constraints ($\bar{g} \geq 0$dB), the *macro-diversity* has detrimental effects on the cooperative network lifetime performance.

References

[1] J. N. Laneman, D. N. C. Tse, G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[2] A. Nosratinia, T.E. Hunter, "Grouping and partner selection in cooperative wireless networks," *IEEE Journ. Sel. Areas Comm.*, vol. 25, no. 2, pp. 369-378, Feb. 2007.

[3] V. Mahinthan, L. Cai, J. W. Mark, X. Shen, "Partner selection based on optimal power allocation in cooperative-diversity systems," *IEEE Trans. Veh. Tech.*, vol. 57, no. 1, pp. 511-520, Jan. 2008.

[4] T. Himsoon, W. P. Siriwongpairat, Z. Han, K. J. R. Liu, "Lifetime maximization via cooperative nodes and relay deployment in wireless networks," *IEEE Journ. Sel. Areas Comm.*, vol. 25, no. 2, pp. 306-317, Feb. 2007.

[5] P. Castiglione, S. Savazzi, M. Nicoli, T. Zemen, "Impact of fading statistics on partner selection in indoor-to-outdoor cooperative networks," to appear in *Proc. IEEE ICC*, May 2010.

[6] W. Chen, L. Dai, K. B. Letaief, Z. Cao, "A unified cross-layer framework for resource allocation in cooperative networks," *IEEE Trans. Wireless Comm.*, vol. 7, no. 8, pp. 3000-3012, Aug. 2008.

[7] G. J. Foschini, J. Salz, "Digital communications over fading radio channels," *Bell Systems Tech. Journ.*, pp. 429–456, Feb. 1983.

[8] Z. Wang, G. B. Giannakis, "A simple and general parametrization quantifying performance in fading channels," *IEEE Trans. Comm.*, vol. 51, no. 8, pp. 1389-1398, Aug. 2003.

[9] S. Savazzi and U. Spagnolini, "Design criteria of two-hop based wireless networks with non-regenerative relays in arbitrary fading channels," *IEEE Trans. Comm.*, vol. 57, no. 5, pp. 1463-1473, May 2009.

[10] C. S. Patel, G. L. Stuber, T. G. Pratt, "Statistical properties of amplify and forward relay fading channels," *IEEE Trans. Veh. Tech.*, vol. 55, no. 1, pp. 1-9, Jan. 2006.

[11] C. Oestges, N. Czink, B. Bandemer, P. Castiglione, F. Kaltenberger, A. J. Paulraj, "Experimental characterization and modeling of outdoor-to-indoor and indoor-to-indoor distributed channels," to appear in *IEEE Trans. Veh. Tech.*.

[12] C. Oestges, B. Clerckx, *MIMO Wireless Communications*, Elsevier Academic Press, 2007.

[13] C. H. Papadimitriou, K. Steiglitz, *Combinatorial optimization: algorithms and complexity*, Dover, New York, NY, USA, 1998.