Impact of Fading Statistics on Partner Selection in Indoor-to-Outdoor Cooperative Networks

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***Abstract*—Cooperative transmission techniques for ad hoc and wireless sensor networks are known to increase the network lifetime. Indeed, the improved spatial diversity allows a more efficient energy usage. Under Rayleigh fading assumption, the selection of cooperative partners is typically based on the knowledge of the average channel power. However, Rayleigh fading is not a suitable model in a large number of practical scenarios, in particular for indoor-to-outdoor applications. In these scenarios additional information of the fading distribution is needed for partner selection. The main focus of this work is to provide an analytical framework to evaluate the impact of the fading statistics on partner selection algorithms. A distributed multi-link channel model is derived from indoor-to-indoor and indoor-to-outdoor channel measurements in order to simulate practical scenarios where the proposed analytical framework is tested. Finally, we introduce a novel partner selection strategy that exploits the distributed knowledge of the effective coding gains provided by the wireless links fading statistics.**

***Index Terms*—Cooperative diversity and coding gains, amplify and forward, grouping algorithms, indoor-to-outdoor channel modeling.**

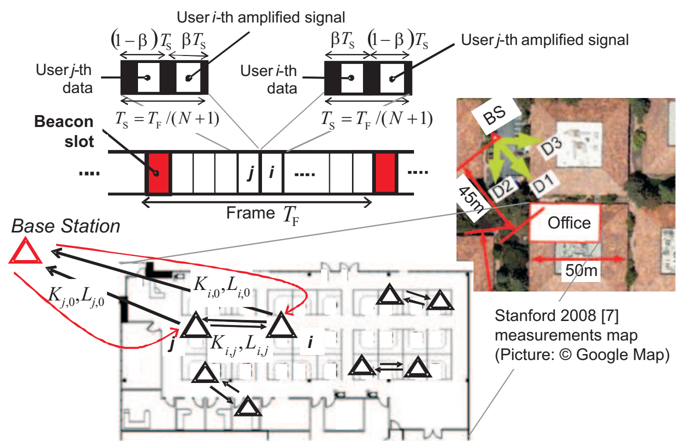

Figure 1. TDMA framing structure (top). Propagation setting (bottom).

I. Introduction

Cooperative communication has been proposed as a method to bring spatial redundancy (or diversity gain) to a network of low-cost, single-antenna devices [1]. Collaborative transmission techniques have been tailored for wireless sensor networks (WSN) where autonomous wireless sensors share their measurements to achieve a global decision and communicate with a base station (BS). The specific scenario considered in this work is the uplink communication between several static sensors and a common BS (or sink node). Battery-powered sensors are distributed indoors (e.g., in an office environment as in Fig. 1), while the BS is located outdoors with external power supply. The sensing nodes are allowed to engage in cooperative transmissions by amplifying and forwarding (AF) to the BS the signals received from the partner nodes.

Before collaborative transmission can start, the nodes shall choose the relay to cooperate with. Relay selection algorithms are usually classified as *reactive* when the source node is in charge of choosing the best relay for its own data [2] or *proactive* when a central coordinator performs (and updates) the partner assignments for each node (centralized grouping [3], [4]). Partner selection is the most interesting and practical problem for medium access control (MAC) layer design. In this paper, we are interested in a proactive scheme where the BS optimally assigns the partner(s) to each node and allocates the transmission resources (e.g., time slots, transmit powers etc.) for each sensing node. The optimality criterion is the minimization of a network goodput metric, e.g. the maximum outage probability or the maximum energy consumption. Assignment algorithms are usually based on the knowledge of second-order fading statistics such as the average channel power, the path-loss or the signal strength [2] [4].

Although Rayleigh fading is typically assumed as a simple and mathematically tractable model for performance evaluation, it is not suitable to model a large number of practical WSN scenarios. Relevant examples are indoor-to-outdoor (I2O) and indoor-to-indoor (I2I) communications [5].

Contribution of this work: we study how the statistics of the channel fading impairment impact on the system performances, in terms of energy consumption, and on the degree of optimality of grouping algorithms. For those scenarios where the Rayleigh fading model does not apply, we address to what extent partner selection algorithms can benefit from the knowledge of the fading distribution more than the only knowledge of the second-order statistic. Performance analysis of partner selection algorithms for arbitrary fading is carried out analytically by using the framework developed in [6] for AF relaying. Results are corroborated using a realistic model

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of the path loss and the small-scale fading statistics, based on I2I and I2O channel measurements at 2.4GHz [7].

II. System Model

The scenario under study consists of N battery-powered nodes that are distributed indoors and communicate with a common BS located outdoors. The BS is acting as destination for all nodes (star network topology). It maintains node synchronization and propagates the framing structure along with the sleep/wake up times for time division multiple access (TDMA). Although TDMA requires specific transmission resources to be reserved for periodic clock drift correction, once synchronization is achieved, each node has an exclusive access to the wireless medium avoiding collisions and idle listening[1]. As shown in Fig. 1, transmissions are organized into frames of duration $T_{\rm F}$, subdivided into $N+1$ slots. A unique slot of duration $T_{\rm S} = T_{\rm F}/(N+1)$ is assigned to each node. One beacon slot is used by the BS to resynchronize the nodes and to configure the transmission policy.

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

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

where ρ_i is the radio frequency (RF) transmit power for node i and σ^2 denotes the variance of the additive white Gaussian noise (AWGN). The fading power is arbitrarily distributed, $|h_{i,j}|^2 \sim f_{h_{i,j}}(x)$, with mean value $\mathbb{E}\left[|h_{i,j}|^2\right] = L_{i,j}^{-1}$ (more details on the fading model are given in Sect. IV).

III. Cooperative Transmission and Outage Analysis

AF relaying is chosen here due to its simplicity (compared to regenerative relaying) and practical implementation. Nodes 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. V. The proposed goodput metric is the energy consumption.

Let (i, j) be a pair of cooperating partners[2], each time slot assigned to any of these two nodes is further sub-divided into two micro-slots. As shown in Fig. 1, for node i the first micro-slot spans a fraction $\beta_i = \beta$ of the available slot duration $T_{\rm S}$. The first micro-slot is reserved for delivering the i-th node data. The second one with duration $(1-\beta)\, T_{\rm S}$ is reserved for transmitting the amplified version of the signal overheard from the partner j. Similarly, for node 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 relay processing is based on "variable gain AF" [9]: node i amplifies the base-band signal received from node j by using an amplification factor $a_i = \sqrt{\rho_i/\left[\sigma^2(\gamma_{j,i}+1)\right]}$ that dynamically varies with the instantaneous SNR $\gamma_{j,i}$ to preserve the power constraint (the transmit power for node i is ρ_i also during the relay phase). Other models for the relay gain are proposed in literature (see e.g. [9]).

Assuming a channel with constant fading for the whole slot duration, the outage probability for node i communicating with node j is $\Pr\left[\gamma_{i,j} < \gamma_{\rm th}^{\rm dir}\right]$ with $\gamma_{\rm th}^{\rm dir} = \left(2^R - 1\right)/\mathcal{A}$, $0 < \mathcal{A} \leq 1$ modeling the modulation and coding format [10] while R refers to the required spectral efficiency.

The outage probability is now evaluated for arbitrary fading by following the approach in [6]. Fading channels are described by two parameters derived from the asymptotic analysis of the random fading power moment generating function (MGF), namely the inherent diversity and the coding gain [6]. The outage probability scales as [11]

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

where $\approx$ indicates that equality holds asymptotically for high SNR[3], $d_{i,j}$ is the diversity order provided by the channel itself, while $c_{i,j}$ is the coding gain. The parameters $d_{i,j}$ and $c_{i,j}$ can be derived from the Laplace transform $\mathcal{F}_{i,j}(s)$ (or MGF) of $f_{|h_{i,j}|^2}(x)$ as (see proof in [6])

$$d_{i,j} \triangleq -\lim_{s\to\infty} \log \mathcal{F}_{i,j}(s)/\log s, \tag{3}$$

$$c_{i,j} \triangleq \left[\Gamma(d_{i,j}+1)/\phi\right]^{1/d_{i,j}} , \tag{4}$$

where $\phi = \lim_{s\to\infty} s^{d_{i,j}} \mathcal{F}_{|h_{i,j}|^2}(s)$ and $\Gamma(x) = \int_0^\infty y^{x-1}\exp(-y)dy$ denotes the complete Gamma function.

Focusing on AF transmission, the SNR for node 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 [9]:

$$\gamma_{(i,j),0} = \gamma_{i,0} + \left(\frac{1}{\gamma_{i,j}} + \frac{1}{\gamma_{j,0}} + \frac{1}{\gamma_{i,j}\gamma_{j,0}}\right)^{-1} . \tag{5}$$

The outage probability

$$\Pr[\gamma_{(i,j),0} < \gamma_{\rm th}^{\rm AF}] \approx \left(\frac{\gamma_{\rm th}^{\rm AF}\sigma^2}{c_{(i,j),0}^{\rm AF}\rho_{(i,j)}}\right)^{d_{(i,j),0}^{\rm AF}} \tag{6}$$

is specified by parameters $d_{(i,j),0}^{\rm AF}$ and $c_{(i,j),0}^{\rm AF}$. 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-node link and the uplink channel. The threshold SNR in (6) is $\gamma_{\rm th}^{\rm AF} = \left(2^{R/\beta_i} - 1\right)/\mathcal{A}_c$, where the spectral efficiency R is increased by multiplying with $1/\beta_i$[4]. The term $\rho_{(i,j)}$ is function of the RF transmit power levels ρ_i and ρ_j.

The outage probability for node j messages is similar to (6) now with $\gamma_{\rm th}^{\rm AF} = \left(2^{R/\beta_j} - 1\right)/\mathcal{A}_c$, diversity and coding gain $d_{(j,i),0}^{\rm AF}$ and $c_{(j,i),0}^{\rm AF}$, respectively.

[1] Collisions and idle listening are the major sources of energy waste in random access networks [8].

[2] We assume that each node can cooperate at most with one partner. The extension of the analysis to grouping assignment with more than one partner can be obtained using a similar approach. It is omitted here for the sake of brevity.

[3] Tightness of the approximation is verified for SNR large enough to guarantee sufficiently low outage probabilities ($\lesssim 10^{-2}$)

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

IV. Wireless Link Performance Modeling

In Sect. IV-A we present a multi-link channel model that both motivates the research of new grouping strategies tailored for fading distributions other than Rayleigh and offers a reliable "test-bed" for evaluating the performances of the new algorithms. Based on the proposed channel model, in Sect. IV-B we introduce a method to evaluate AF link performances.

A. I2I and I2O Ricean fading model

The model is based on the channel measurement campaign [7] carried out in an office environment at 2.4 GHz (see Fig. 1). Small-scale fading that impairs the I2I inter-node channels and the I2O uplink (relayed) channels from the *static* nodes to the BS is well approximated by a Ricean distribution [12]. Herein, we simplify the model of [5] by considering only the static shadowing as part of the path loss, neglecting the dynamic component. The parameters describing the link (i, j) channel, i.e. the path loss $L_{i,j}$ and the K-factor $K_{i,j}$, are modeled as correlated log-normal random variables, with mean values depending on the link distances $D_{i,j}$, as defined in the sequel.

For the I2I inter-node links ($j \neq 0$) $L_{i,j}$ and $K_{i,j}$ are chosen as in [5, (17) and (20)]. On the other hand, for the I2O link $(i, 0)$ from the node i to the BS ($j = 0$) we adopt the model [5], here completed with the support of [13], [14]. According to the outdoor-to-indoor (O2I) urban micro-cell scenario B4 in [13], the propagation is modeled as the combination of three main contributions: the outdoor propagation from the BS to the nearest wall (here indicated by the superscript Out); the propagation through the cited wall (W); the indoor propagation from the wall to the node (In). These three radio links are described, respectively, by the path loss and K-factor parameters: $\left(L^{\mathrm{Out}}_{i,0}, K^{\mathrm{Out}}_{i,0}\right)$, $L^{\mathrm{W}}_{i,0}$ and $\left(L^{\mathrm{In}}_{i,0}, K^{\mathrm{In}}_{i,0}\right)$. All parameters are here expressed in decibel (dB). The overall link path loss $L_{i,0}$ and K-factor $K_{i,0}$ are modeled as

$$L_{i,0} = L^{\mathrm{Out}}_{i,0} + L^{\mathrm{W}}_{i,0} + L^{\mathrm{In}}_{i,0}, \tag{7}$$

$$K_{i,0} = K^{\mathrm{Out}}_{i,0} + K^{\mathrm{In}}_{i,0}. \tag{8}$$

Notice that the wall contribution does not appear in (8) as it has no effects on $K_{i,0}$. Conversely, $L^{\mathrm{W}}_{i,0} = 14\mathrm{dB}$ accounts for the path loss due to the wall (neglecting the angle of the propagation path with respect to the wall [13]). The outdoor parameters $\left(L^{\mathrm{Out}}_{i,0}, K^{\mathrm{Out}}_{i,0}\right)$ are modeled according to [14, (4) and (9)] (here slightly manipulated):

$$L^{\mathrm{Out}}_{i,0} = L^{\mathrm{Out}}_{\mathrm{ref}} + 38.86 \log_{10} \frac{D_{i,0}}{D^{\mathrm{Out}}_{\mathrm{ref}}} + \bar{L}^{\mathrm{Out}}_{i,0}, \tag{9}$$

$$K^{\mathrm{Out}}_{i,0} = 7.83 - 4.51 \log_{10} \frac{D_{i,0}}{D^{\mathrm{Out}}_{\mathrm{ref}}} - 0.24\bar{L}^{\mathrm{Out}}_{i,0} + \bar{K}^{\mathrm{Out}}_{i,0}, \tag{10}$$

where $L^{\mathrm{Out}}_{\mathrm{ref}} = 135.78\mathrm{dB}$ is the outdoor path loss at the reference distance $D^{\mathrm{Out}}_{\mathrm{ref}} = 1\mathrm{km}$, $D_{i,0}$ is the distance [km] between the node i and the BS, while $\bar{L}^{\mathrm{Out}}_{i,0} \sim \mathcal{N}(0,\, 7.96\mathrm{dB})$ and $\bar{K}^{\mathrm{Out}}_{i,0} \sim \mathcal{N}(0,\, 7.24\mathrm{dB})$ are zero-mean Gaussian variates with standard deviations 7.96dB and 7.24dB, respectively. The indoor parameters $\left(L^{\mathrm{In}}_{i,0}, K^{\mathrm{In}}_{i,0}\right)$ are modeled according to scenario B4 in [13] and to [5], respectively:

$$L^{\mathrm{In}}_{i,0} = 0.5\, D_{i,\mathrm{W}} + \bar{L}^{\mathrm{In}}_{i,0}, \tag{11}$$

$$K^{\mathrm{In}}_{i,0} = -0.60\, L^{\mathrm{In}}_{i,0} + \bar{K}^{\mathrm{In}}_{i,0}, \tag{12}$$

where $D_{i,\mathrm{W}}$ is the distance [m] between the node i and the wall, $\bar{L}^{\mathrm{In}}_{i,0} \sim \mathcal{N}(0,\, 7\mathrm{dB})$ and $\bar{K}^{\mathrm{In}}_{i,0} \sim \mathcal{N}(0,\, 3.8\mathrm{dB})$. The I2O and I2I path losses $L_{i,0}$ and $L_{i,j}$ are further scaled respectively by -15 dB and -8 dB to include the antenna gains.

B. Effective coding gain for AF relaying

The outage probability analysis is now tailored according to the channel model outlined in the previous section. For Ricean fading, the outage probability for source i cooperating with partner j through AF relaying is given in (6), with $\rho_{(i,j)} = \sqrt{\rho_i \rho_j}$, $d^{\mathrm{AF}}_{(i,j),0} = \min\left[d_{i,j}, d_{j,0}\right] + d_{i,0} = 2$ and the *effective coding gain* [6]

$$c^{\mathrm{AF}}_{(i,j),0} = \left[\frac{1}{2c_{i,0}}\left(\frac{1}{c_{i,j}} + \frac{1}{c_{j,0}}\right)\right]^{-\frac{1}{2}}. \tag{13}$$

The above coding gain measures the power gain that would be available to node i in case partner j is chosen to amplify and forward its own signal. It depends on the gains $c_{i,j}$, $c_{i,0}$ and $c_{j,0}$ provided over each link involved in cooperative transmission. In particular, using (4) and [6]:

$$c_{i,j} = \frac{1}{\lim_{s\to\infty} s\mathcal{F}_{|h_{i,j}|^2}(s)} = \frac{\exp\left(K_{i,j}\right)}{L_{i,j}\left(K_{i,j}+1\right)}, \tag{14}$$

where $\mathcal{F}_{|h_{i,j}|^2}(s)$ is the MGF of the fading squared envelope that can be expressed, for Ricean fading, as a function of the K-factor $K_{i,j}$ and path loss $L_{i,j}$ terms [12].

In order to model the parameter $c^{\mathrm{AF}}_{(i,j),0}$ for the generic node pair (i, j), we now use the I2I/I2O models introduced in Sect. IV-A for each inter-node/uplink channel. We evaluate the parameters $(K_{i,j}, L_{i,j})$ according to the channel models. Then, we compute the respective coding gains for all involved links according to (14) and insert them in (13).

To provide more insight on AF link performance analysis, let us first analyze the coding gain (14) that is computed using the $(K_{i,j}, L_{i,j})$ values estimated (per link and frequency bin with the estimators employed in [5]) from the real channel measurements [7]. Fig. 2 plots the calculated coding gains $c_{i,j}$ for the I2I and I2O links over the estimated path loss $L_{i,j}$. Dashed lines show the coding gain curve $c_{i,j} = L^{-1}_{i,j}$ that would be expected under the Rayleigh fading assumption, i.e. for $K_{i,j} = 0$ in (14): the observed coding gains are clearly larger than those expected for Rayleigh fading, in particular for decreasing path loss.

On the other hand, solid lines show the coding gain fitting derived under the Ricean fading assumption as follows. According to the model proposed in [5] and outlined in Sect. IV-A, the K-factor measured in dB is Gaussian distributed around a path loss dependent mean. The latter is determined by a least mean square error regression curve of the estimated $(K_{i,j}, L_{i,j})$ values and is inserted in (14), obtaining the fitting of the coding gains $c_{i,j}$ represented by the solid lines. Clearly, Rayleigh fading holds true only if the path loss is large, whereas, for lower path losses, the coding gain is better fitted by (14). It is important to mention that the values of the individual path loss (and subsequently of the coding gains) are relative to each other in Fig. 2, since no reference path loss was measured in [7].

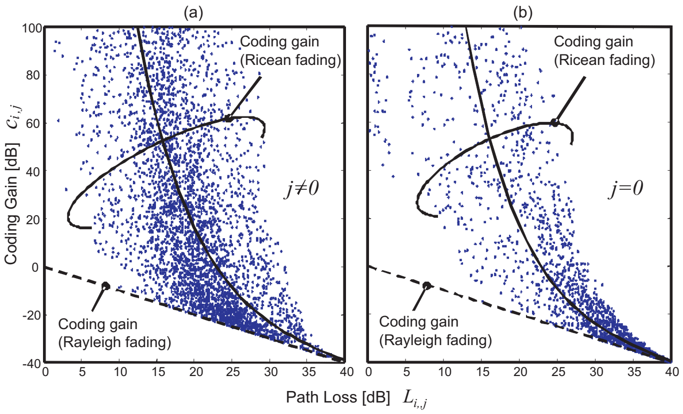

Figure 2. Coding gains (relative values) for (a) the inter-node I2I and for (b) the uplink I2O channels over the measured relative path loss.

Even if rather simple, the above analysis suggests that in practical I2O scenarios, where Rayleigh fading is a bad model to describe the link performances (particularly for low path loss values and static nodes), the evaluation of the error probability over the wireless channel (that impacts on the partner assignment algorithm) should be based on a more precise information about the coding and diversity gains provided by each collaborative link, more than on the simpler information about the experienced link path loss. To further explore this aspect, in the following section the effective coding gain $c^{\mathrm{AF}}_{(i,j),0}$ defined in (13), for a given node pair (i, j), is proposed as the key metric to evaluate the optimal node pairing.

V. Partner Selection Strategies

The problem we tackle is how to pair (or leave single) the nodes that are allowed to communicate to the outdoor BS. The aim is to maximize the network lifetime. Hence, the optimization metric, used for partner selection, is the maximum energy consumed by the devices over the frame[5]. Without loss of generality, Gaussian modulation ($\mathcal{A} = \mathcal{A}_c = 1$) is assumed[6].

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

$$E_{i,0} \approx \frac{\gamma^{\mathrm{dir}}_{\mathrm{th}} \sigma^2}{c_{i,0}} \frac{T_{\mathrm{S}}}{p}, \tag{15}$$

where the consumption of the micro-processor and the periodic resynchronization is assumed negligible and it is omitted.

Energy consumption for cooperating nodes. The transmit energy for cooperating devices is chosen so that the outage probability at the BS for both nodes is lower or equal to p. The following remark allows to compute the required RF power level for the cooperating nodes to satisfy the outage constraint. Notice that as a practical assumption, the RF transmit power level is kept constant over the reserved time slot[7].

[5]Minimizing this metric is shown to maximize the network lifetime, assuming that battery capacity is the same for all the nodes.

[6]This assumption does not significantly impact on the performance comparison between the partner selection algorithms.

[7]To avoid amplifier non-linearities.

Remark 1: For small enough p, the required RF transmit power levels to achieve the outage probability p are:

$$\rho_i = \rho_j = \rho_{(i,j)} = \kappa(\hat{\beta})\sigma^2/\sqrt{p}, \tag{16}$$

where

$$\kappa(\beta) = \max\left[\left(2^{R/\beta} - 1\right)/c^{\mathrm{AF}}_{(i,j),0}, \left(2^{R/(1-\beta)} - 1\right)/c^{\mathrm{AF}}_{(j,i),0}\right] \tag{17}$$

and the optimal micro-slot fraction $\hat{\beta}$ is the solution to

$$\left(2^{R/\hat{\beta}} - 1\right) c^{\mathrm{AF}}_{(j,i),0} = \left(2^{R/\left(1-\hat{\beta}\right)} - 1\right) c^{\mathrm{AF}}_{(i,j),0}. \tag{18}$$

If $c_{i,j} \gg \max\left[c_{i,0}, c_{j,0}\right]$, the micro-slots have equal length, $\hat{\beta} \approx 1/2$, therefore $\rho_{(i,j)} = \kappa(1/2)\sigma^2/\sqrt{p}$. For the proof, see the Appendix.

According to Remark 1, each of the cooperating nodes uses a power equal to (16) during the reserved slot of duration T_{S}. The overall energy consumption for node i cooperating with j is defined as

$$E^{\mathrm{AF}}_{(i,j),0} \approx \rho_{(i,j)} T_{\mathrm{S}} + \rho_{RX}\left(1 - \beta_i\right) T_{\mathrm{S}} + E^{\mathrm{AF}}_{\mu\mathrm{p}}, \tag{19}$$

where $E^{\mathrm{AF}}_{\mu\mathrm{p}}$ is the increased energy consumption of the amplifying circuitry, ρ_{RX} accounts for the absorbed power in receiving mode. Recall that node i overhears the partner's channel during the micro-slot of duration $\left(1 - \beta_i\right) T_{\mathrm{S}}$. The energy needed by node j cooperating with i is $E^{\mathrm{AF}}_{(j,i),0}$.

According to the I2O performance modeling in Sect. IV, it is likely that $c_{i,j} \gg \max\left[c_{i,0}, c_{j,0}\right]$. It follows from Remark 1, that in our scenario the optimal choice is to set an equal duration for all the micro-slots, i.e. $\beta_i = \beta_j = 1/2$.

A. Optimal pairing for the min-max energy consumption

Define the set of candidate pairing sets $\mathcal{P}$, such that one set $\xi \in \mathcal{P}$ contains up to $\lfloor N/2 \rfloor$ *disjoint* pairs of cooperative nodes: $\xi = \{(i,j),(k,h),...,(f,g)\}$. All the non-paired nodes belong to the set of single nodes $\mathcal{S}_\xi = \{q, s, \ldots, z\}$, such that $2\left|\xi\right| + \left|\mathcal{S}_\xi\right| = N$ (where symbol $|\cdot|$ stands for the cardinality of the set). Given the candidate pairing set ξ and the corresponding single node set $\mathcal{S}_\xi$, the maximum energy consumed by a node in the network is $E^{\max}(\xi) = \max[\max_{(i,j)\in\xi} E^{\max}_{(i,j),0}, \max_{q\in\mathcal{S}_\xi} E_{q,0}]$, 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

$$\hat{\xi} = \arg\min_{\xi\in\mathcal{P}} E^{\max}(\xi). \tag{20}$$

The problem (20) can be formulated as a special case of the weighted matching problem on the non-bipartite graph $\mathcal{G} = (\mathcal{X}, \mathcal{E})$ [15]. The set of vertices $\mathcal{X}$ corresponds to the set of nodes $\{1, \ldots, N\}$, which are fully connected by the set of undirected edges $\mathcal{E} = \{e_{i,j} : (i, j \in \mathcal{X})\ \&\ (i \leq j)\}$. 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 $w\left(e_{i,j<i}\right) = E^{\max}_{(i,j),0}$ and $w\left(e_{i,j=i}\right) = E_{i,0}$ are associated to all the edges and loops, respectively.

An optimal algorithm to solve this problem can be found in [3], referred therein as *maximum minimum* utility strategy.

Since our problem formulation is in the *min-max* utility form, trivial changes must be applied to the solution in [3]. The algorithm removes at each iteration the maximum weighted edge and checks the existence of a perfect matching solution in the remaining graph. In our case the algorithm that checks the existence of a perfect matching is the one proposed by Gabow as referenced in [15, Ch. 11] for the non-bipartite weighted matching problem, instead of the Hungarian method, which is tailored for the bipartite graphs considered in [3].

The above algorithm for finding the minimum maximum utility reaches the solution in $O\left(N^5\right)$ computational time. Indeed, the number of iterations is in the order of the number of edges $O\left(N^2\right)$ since the graph is complete. The Gabow algorithm, with complexity $O\left(N^3\right)$, is performed at each iteration, leading to the overall complexity $O\left(N^3\right)\times O\left(N^2\right) = O\left(N^5\right)$.

B. Worst-link-first coding-gain-based (WLF-CG) algorithm

The optimal algorithm requires the BS to know all the inter-node coding gains for computing $c^{\mathrm{AF}}_{(i,j),0}$ for all the AF "logical links" $(i,j)\,,0$. In this work, a modified version of the worst-link-first (WLF) algorithm [4] is tailored here for the I2O environment and the proposed MAC protocol, reducing the complexity to $O\left(N^2\right)$. The conventional WLF algorithm (referred to as WLF path-loss-based, WLF-PL) is based on the information of second order statistics of the fading impairment. Our algorithm is based instead on a more complete information of the propagation environment, described by the coding gains of the cooperative links (WLF coding-gain-based, WLF-CG). The algorithm is composed of two phases: a distributed phase where local information about the propagation environment is collected by the devices and forwarded to the BS and a centralized one where the BS finalizes the pairing decisions.

In the distributed phase, each node i computes the coding gains $c_{i,0}$ and $c_{i,j}$ from the estimated K-factor and path loss values of the respective links. The ratio $c_{i,j}/c_{i,0}$ is compared at each node i to a common threshold in order to guarantee the condition $c_{i,j} \gg c_{i,0}$. If $c_{i,j}/c_{i,0}$ is above the threshold, node j becomes a candidate partner for node i. Finally, each node i communicates to the BS the set of candidate partners.

In the centralized phase, the BS builds a sorted list of nodes from the smallest (worst-uplink) to the largest uplink coding gain (best-uplink). For even number of nodes, at each iteration the BS assigns to the worst-uplink node its best-uplink candidate partner[8], if there is one, and removes the paired nodes from the list. If no candidate partners are available for the worst-uplink node, the BS leaves the node single and removes it from the list.

The algorithm is slightly modified if the number of nodes in the network is odd. In this case, as very first step of the centralized phase, the BS lets the best-uplink node remain single and removes it from the list. The algorithm proceeds with the centralized phase as described for even nodes.

In the next section, the WLF-CG performance is compared to that of the WLF-PL algorithm, that works here in the same way but with the metric $L^{-1}_{i,j}$ instead of $c_{i,j}$.

[8]The assignment is carried out regardless of the choice of candidate partners made by the best-uplink node.

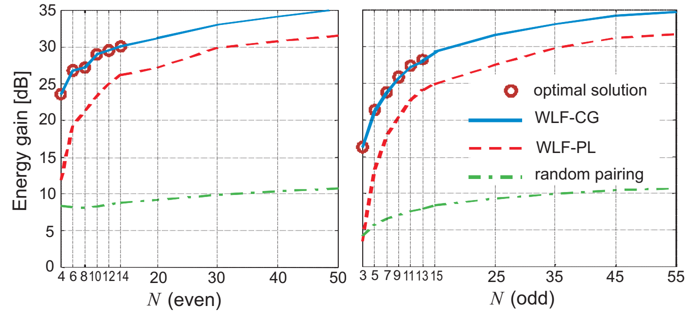

Figure 3. Energy saving provided by cooperation with respect to the non-cooperative transmission.

VI. Simulation Results

In this section we simulate the performances of the partner selection algorithms in Sect. V. The simulated network topology reproduces, with some simplifications, the one in [7] as depicted in Fig. 1. Performance results are averaged over 5×10^4 scenarios. For each scenario, N nodes are randomly distributed in a $25\mathrm{m} \times 25\mathrm{m}$ indoor environment, while the BS is placed outdoors $50\mathrm{m}$ away from the nearest wall (for simplicity, the I2O links are assumed to be perpendicular to the wall, see Fig. 1). The parameters $(L_{i,j}, K_{i,j})$ values associated to every I2I and I2O link are generated according to the stochastic model in Sect. IV-A. The target outage probability is $p = 10^{-3}$ for all the nodes with spectral efficiency $R = 1\,\mathrm{bps/Hz}$.

Fig. 3 shows the ratio between the maximum energy consumptions, averaged among the scenarios, for the non-cooperative and cooperative systems. This ratio 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 obtained using one of the illustrated partner selection algorithms. The optimal pairing solution (20) is compared with the random pairing strategy[9], the greedy algorithms WLF-PL and WLF-CG. According to the simulated I2O uplink scenario, the candidate partner conditions $c_{i,j} \gg c_{i,0}$ (for the WLF-CG) and $L_{i,j} \ll L_{i,0}$ (for the WLF-PL) are almost guaranteed for each pair of nodes, therefore no threshold is defined for the distributed phase of the WLF algorithms. Fig. 3 shows that the proposed WLF-CG algorithm gains from $11\mathrm{dB}$ $(N=4)$ to $4\mathrm{dB}$ $(N=50)$ compared to the WLF-PL, and reaches almost always the optimal solution. The WLF-CG outperforms the WLF-PL also for odd N, achieving the optimal solution in almost all scenarios[10]. Both greedy algorithms outperform remarkably the random pairing, which requires even more energy than the direct transmission in some scenarios. Also notice that for small networks $(N<10)$ the pairing strategies achieve larger gains for even N, since

[9]All nodes are randomly paired with each other, the pairs being disjoint. In case of odd N, one randomly chosen node remains single.

[10]The WLF-CG outperforms the WLF-PL due to its more precise metric. On the other hand, the degree of optimality increases for both algorithms in inverse proportion to the sensitivity of the optimal solution to the inter-node links coding gain values $c_{i,j}$. Since this sensitivity is in our model extremely low $(c_{i,j} \gg c_{i,0})$, the WLF-CG is almost optimal.

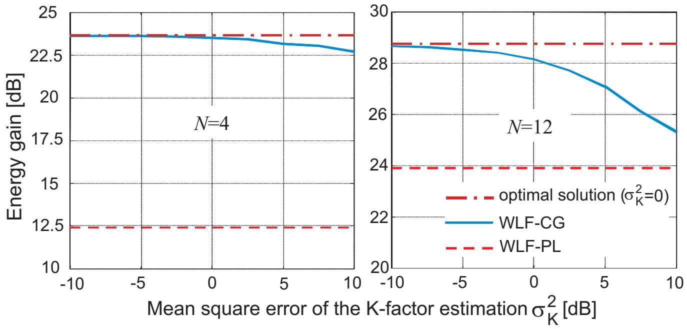

Figure 4. WLF-CG performance for varying σ_K^2.

the performances for odd N are likely dominated by those experienced by the unpaired node.

The proposed WLF-CG algorithm shows large energy gains compared to direct transmission, from 16 to 35dB. We expect these gains to be smaller in practice, since the energy consumption increases in AF mode (e.g. for receiving and amplifying partner messages[11]). Slot-splitting also translates into a penalty factor for AF, compared to the non-cooperative case, as it typically increases the protocol over-head.

The estimation of the K-factors, required by the WLF-CG, does not add much more complexity compared to estimating only the path losses. Moreover, it is robust to AWGN and shadowing [16]. Since the coding gain (14) is very sensitive to the K-factor estimation error, in Fig. 4 we study the impact of this error on the performance of the WLF-CG algorithm. The estimation error is modeled as AWGN, whose distribution $\mathcal{N}\left(0, \sigma_K^2\right)$ is truncated to guarantee positive K-factor estimates. Fig. 4 shows the energy saving provided by cooperation with respect to the non-cooperative transmission for varying mean square error σ_K^2. The results suggest that for $N \lesssim 12$, the WLF-CG retains better performance compared to the WLF-PL if $\sigma_K^2 \lesssim 10\text{dB}$. The interesting conclusion is that the WLF-CG is robust for small networks, whereas, for large ones, it is more sensitive to the K-factor estimation errors.

VII. Concluding Remarks

In this paper we investigated the performance, in terms of energy consumption, of different partner selection algorithms over wireless links with a significant deterministic fading component. We provided a new analytical framework based on the outage analysis of the AF relaying scheme [6]. Realistic coding gains values, here evaluated from measured I2I and I2O channels [7], highlight the poorness of the Rayleigh fading model in distributed communications where the nodes are static. Therefore, we proposed a novel partner selection strategy that exploits the local knowledge not only of the path losses but also of the fading statistics, i.e. the K-factors. In practical I2O scenarios [5], the novel low complexity algorithm WLF-CG gains from 3 to 11dB, depending on the size of the network, compared to existing algorithms [4]. Finally, for small networks, we verified the robustness of the proposed algorithm to K-factor estimation errors.

[11] In the simulations, ρ_{RX} and $E_{\mu\text{p}}^{\text{AF}}$ are set to 0 for simplicity.

Appendix

Proof of Remark 1: The required upper-limit p to the outage probability (6), where $\rho_{(i,j)} = \sqrt{\rho_i \rho_j}$ and $d_{(i,j),0}^{\text{AF}} = 2$, constrains the powers ρ_i and ρ_j over the two micro-slots such that (for $\beta_i = \beta$ and $\beta_j = 1 - \beta$):

$$\begin{aligned} \rho_j &\geq \left[\sigma^2 \left(2^{R/(1-\beta)} - 1\right) / c_{(j,i),0}^{\text{AF}}\right]^2 (p \cdot \rho_i)^{-1}, \\ \rho_i &\geq \left[\sigma^2 \left(2^{R/\beta} - 1\right) / c_{(i,j),0}^{\text{AF}}\right]^2 (p \cdot \rho_j)^{-1}. \end{aligned} \quad (21)$$

Minimizing the maximum over ρ_i and ρ_j leads to the straightforward solution $\rho_i = \rho_j = \kappa(\hat{\beta})\sigma^2/\sqrt{p}$. The optimal micro-slot fraction $\hat{\beta}$ is found such that $\hat{\beta} = \arg\min_\beta \kappa(\beta)$ and is the solution to (18). Notice that for $c_{i,j} \gg \max\left[c_{i,0}, c_{j,0}\right]$, the AF effective coding gain $c_{(i,j),0}^{\text{AF}} \approx c_{(j,i),0}^{\text{AF}}$ and the optimal fraction, solution to (18), is $\hat{\beta} \approx 1/2$. ■

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