Energy-Efficient Relay Assignment and Power Control in Multi-User and Multi-Relay Networks

A. Zappone, *Senior Member, IEEE*, S. Atapattu, *Member, IEEE*, M. Di Renzo, *Senior Member, IEEE*, J. Evans, *Senior Member, IEEE*, and M. Debbah, *Fellow, IEEE*

***Abstract*—We consider a multiuser multirelay network where each source communicates with its destination via an assigned relay. To ensure fairness among the users, the minimum of the users' energy efficiencies (in bit-per-Joule) is jointly maximized with respect to the relay assignment and transmit power of both source and relay nodes. The resulting algorithm is provably convergent, requires limited complexity, and significantly outperforms the baseline scenario in which no joint optimization of transmit powers and relay assignment is performed.**

***Index Terms*—Energy efficiency, multi-user networks, multi-relay networks, relay assignment, power optimization.**

I. Introduction

RADIO resource allocation for energy efficiency (EE) has become a key performance indicator for the design of future mobile networks [1]. Furthermore, the use of relays constitutes a fundamental tool for extending the coverage of current and future wireless networks [2]. In the context of single- or multi-user networks, where multiple relays are available, properly designed relay assignment strategies have the potential of providing spatial diversity gains to the users, thus improving their performance [3]. The relay assignment problem is usually formulated to improve the error rate and throughput of the source-to-destination links, by assuming that their transmit powers are fixed, e.g., [4] and [5]. The rise of EE as a key performance indicator for wireless networks, however, has put forth the relevance of investigating the relay assignment problem from an EE perspective.

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A. Zappone is with LANEAS Group, L2S Department, CNRS, CentraleSupélec, University of Paris-Sud, Université Paris-Saclay, 91192 Gif-sur-Yvette, France (e-mail: alessio.zappone@l2s.centralesupelec.fr).

S. Atapattu and J. Evans are with the Department of Electrical and Electronic Engineering, University of Melbourne, Melbourne, VIC 3010, Australia (e-mail: saman.atapattu@unimelb.edu.au; jse@unimelb.edu.au).

M. Di Renzo is with L2S Department, CNRS, CentraleSupélec, University of Paris-Sud, Université Paris-Saclay, 91192 Gif-sur-Yvette, France (e-mail: marco.direnzo@l2s.centralesupelec.fr).

M. Debbah is with LANEAS Group, L2S Department, CNRS, CentraleSupélec, University of Paris-Sud, Université Paris-Saclay, 91192 Gif-sur-Yvette, France, and also with the Mathematical and Algorithmic Sciences Laboratory, Huawei France Research and Development, 92100 Paris, France (e-mail: merouane.debbahg@l2s.centralesupelec.fr).

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The design of relay assignment schemes that aim at EE optimization is considered in several recent works focused on single-user networks [6]–[10] (and references therein). In [11], a power-allocation method that reduces the total power consumption while maintaining the required quality of service for application to single-user and multi-user relay systems is proposed. Other recent works study power allocation schemes for relay-aided networks, considering a fixed assignment. In [12], the EE of a multi-user and single-relay MIMO system is maximized. In [13], a relay-assisted cognitive system is considered. An information-theoretic analysis of the multi-way relay channel is available in [14]. Energy-efficient resource allocation policies for the multi-way relay channel are studied in [15]. In [16], schemes that minimize the energy expenditure of cloud radio relay-assisted networks under quality of service constraints are analyzed.

In the depicted context, this letter considers a multi-user and multi-relay network, and aims at *jointly* optimizing the relay assignment and transmit powers to maximize the minimum bit-per-Joule EE across the users, a problem that has not been considered in previous works. Indeed, as outlined above, most previous works are focused only on either relay assignment or power control. Moreover, available works that jointly consider relay assignment and power control are focused on non-energy-efficient allocations, like [17], where a joint optimization of relay selection and resource allocation under rate constraints is considered.

The novel scenario considered in this letter leads to a mixed-integer optimization problem, which is tackled by generalizing to the energy-efficient scenario the relay assignment strategies from [5], where SNR maximization was considered, and by employing generalized fractional programming tools to deal with the power allocation part of the problem [1].

II. System Model

We consider the dual-hop wireless relay network depicted in Fig. 1, where K source nodes $(S_1, \dots, S_K)$ send information to their corresponding destination nodes $(D_1, \dots, D_K)$ via N relay nodes $(R_1, \dots, R_N)$ that operate either in decode-and-forward (DF) or in amplify-and-forward (AF) mode. Each node is equipped with a single antenna and operates in half-duplex mode. The transmit powers of the kth user and nth relay, $n \in \{1, \dots, N\}$, are p_k and q_n, respectively. Motivated by practical considerations, we consider the case in which each user is assisted by one and only one relay,[1] thus assuming $N \geq K$. To avoid interference among the users, orthogonal channels are used for transmission. The fading channel between S_k and R_n and between R_n and D_k are denoted by $f_{k,n}$ and $g_{k,n}$, respectively. All channels

[1]Having multiple users associated to multiple relays would increase the system complexity and energy consumption [18], [19].

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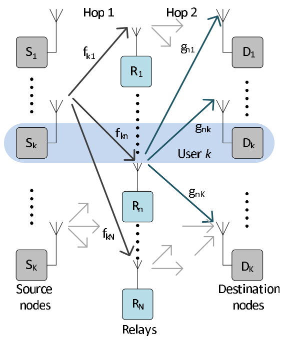

Fig. 1. Considered multi-user multi-relay network model.

are assumed to be independent and identically distributed, to remain constant during one transmission block, but to change independently over different transmission blocks. Moreover, the direct user-destination channels are assumed to be too weak for communication and hence are neglected. Then, the achievable rate, $r_{k,n}$, and bit-per-Joule EE, $\eta_{k,n}$, of the k-th user-destination pair are:

$$r_{k,n}=\frac{1}{2K}\log_2\big(1+\gamma_{k,n}(p_k,q_n)\big)\ [\text{bpcu}] \tag{1}$$

$$\eta_{k,n}=\frac{B\log_2\big(1+\gamma_{k,n}(p_k,q_n)\big)}{\lambda_k p_k+\mu_n q_n+P_{k,n}^{(c)}}\ [\text{bit/Joule}] \tag{2}$$

where "bpcu" stands for bit per channel use, the pre-log factor $1/2K$ is due to the half-duplex operation mode and to the use of orthogonal transmission channels, λ_k and μ_n are the inverse of the power amplifier efficiencies of S_k and R_n, respectively, $P_{k,n}^{(c)}$ is the static power dissipated to operate the communication of user k through relay n, and $\gamma_{k,n}$ is the SNR of the S_k-D_k pair through relay R_n, which depends on the particular relaying protocol being used. Let $\gamma_{k,n}^{(1)}=p_k\frac{|f_{k,n}|^2}{\sigma^2}$ and $\gamma_{k,n}^{(2)}=q_n\frac{|g_{k,n}|^2}{\sigma^2}$, be the SNRs of the S_k-R_n and R_n-D_k links, where σ^2 is the noise power. The SNRs obtained using the DF and AF relaying protocols are, respectively:

$$\gamma_{k,n}^{DF}(p_k,q_n)=\min\Big(\gamma_{k,n}^{(1)},\gamma_{k,n}^{(2)}\Big)=\frac{\min\big(p_k|f_{k,n}|^2,q_n|g_{k,n}|^2\big)}{\sigma^2} \tag{3}$$

$$\gamma_{k,n}^{AF}(p_k,q_n)=\frac{\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)}}{\gamma_{k,n}^{(1)}+\gamma_{k,n}^{(2)}+1}=\frac{p_k q_n|f_{k,n}|^2|g_{k,n}|^2/\sigma^2}{p_k|f_{k,n}|^2+q_n|g_{k,n}|^2+\sigma^2}. \tag{4}$$

For fairness reasons,[2] our goal is to maximize the minimum EE across the users, with respect to $\{p_k\}_{k=1}^K$, $\{q_n\}_{n=1}^N$, and to the source-relay association variables $\{\delta_{k,n}\}_{k,n}$, where $\delta_{k,n}=1$ if user k is assisted by relay n, and $\delta_{k,n}=0$ otherwise.

III. Problem Formulation and Solution

The k-th user's EE before knowing its associated relay is:

$$\eta_k=B\frac{\sum_{n=1}^N\log_2\big(1+\delta_{k,n}\gamma_{k,n}(p_k,q_n)\big)}{\lambda_k p_k+\sum_{n=1}^N\delta_{k,n}\Big(\mu_n q_n+P_{k,n}^{(c)}\Big)}\ . \tag{5}$$

Then, neglecting the inessential factor B, the maximization of the minimum EE among the users is:

$$\max_{\{p_k,q_n,\delta_{k,n}\}_{k,n}}\ \min_{1\le k\le K}\eta_k(p_k,q_n,\delta_{k,n}) \tag{6a}$$

[2]If instead a system-wide performance optimization is desired, the system global EE is a more suitable performance metric.

Algorithm 1 Alternating Maximization of the Problem in (6)

Set $\{\bar\delta_{k,n}\}_{k,n}\in\{0,1\}^{KN}$;
repeat
$\{\bar p_k,\bar q_n\}_{k,n}=\arg\max_{\{p_k,q_n\}_{k,n}}\min_{1\le k\le K}\mathrm{EE}_k(p_k,q_n,\bar\delta_{k,n})$, subject to (6b);
$\{\bar\delta_{k,n}\}_{k,n}=\arg\max_{\{\delta_{k,n}\}_{k,n}}\min_{1\le k\le K}\mathrm{EE}_k(\bar p_k,\bar q_n,\ \delta_{k,n})$, subject to (6c);
until convergence

$$\text{s.t. } p_k\in[0,p_{max,k}]\ ,\ q_n\in[0,q_{max,n}]\ \forall k,n \tag{6b}$$

$$\delta_{k,n}\in\{0,1\},\textstyle\sum_{n=1}^N\delta_{k,n}=1,\sum_{k=1}^K\delta_{k,n}\in\{0,1\}\ \forall k,n \tag{6c}$$

where $p_{max,k}$ and $q_{max,n}$ are the maximum power levels of S_k and R_n, respectively, while (6c) ensures that each user is connected to one and only one relay.

The main challenges to solve (6) lie in its mixed-integer nature and in its non-concave fractional objective, which is not differentiable even with respect to only the transmit powers due to the $\min(\cdot)$ operator. We tackle these issues by using the alternating optimization method illustrated in Algorithm 1, iteratively optimizing the association variables $\{\delta_{k,n}\}_{k,n}$ for fixed transmit powers $\{p_k,q_n\}_{k,n}$, and the transmit powers for fixed association variables, until convergence.

Algorithm 1 monotonically increases the value of the objective and converges in the value of the objective,[3] even though global optimality cannot be theoretically guaranteed. The two optimization subproblems that constitute Algorithm 1 are discussed and solved in the next two sections.

A. Transmit Power Optimization

If the association variables $\delta_{k,n}=\bar\delta_{k,n}$ are fixed for all *k, n*, the optimization with respect to $\{p_k\}_k$ and $\{q_n\}_n$ is stated as:

$$\max_{\{p_k,q_n\}_{k,n}}\ \min_{1\le k\le K}\eta_k(p_k,q_n,\bar\delta_{k,n}) \tag{7a}$$

$$\text{s.t. } p_k\in[0,p_{max,k}]\ ,\ [0,q_{max,n}]\ \forall k,n\ . \tag{7b}$$

The optimization problem in (7) is an instance of a generalized fractional program [20], which differs from the well-known class of fractional programs because of the presence of the $\min(\cdot)$ operator. An algorithm to globally solve generalized fractional programs was proposed in [20, Sec. 2.2] and named *generalized Dinkelbach's algorithm*. If each ratio within the $\min(\cdot)$ operator has a concave numerator and a convex denominator, and all the constraints are convex, then the generalized Dinkelbach's algorithm finds the solution of (7) by solving a sequence of convex auxiliary problems that converge at a rate that is at least linear [20, Proposition 3.3]. As far as the specific problem at hand is concerned, the denominators in (7a) and the affine constraints in (7b) fulfill these requirements. Instead, as for the numerators in (7a), the analysis is more challenging. In particular, the DF and AF protocols need to be treated separately.

Proposition 1: Let the DF protocol be used. Every numerator in (7a) is jointly concave in p_k and q_n, for all k,n.

Proof: It needs to be proved that $\gamma_{k,n}$ is jointly concave in p_k and q_n, for all k,n. This follows since the logarithm of a concave function is concave and the sum of concave functions is concave. Also, $\gamma_{k,n}$ in (3) is the minimum of linear functions and, thus, it is concave, since the minimum of concave functions is concave. ■

[3]The objective (6a) is upper-bounded over the feasible set and thus it cannot increase indefinitely.

Proposition 2: With the AF protocol, every numerator in (7a) is jointly concave in p_k, q_n if $\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)} \geq \frac{1}{2}$ for all *k, n*.

Proof: Similar to DF, it needs to be proved that $\gamma_{k,n}$ is jointly concave in p_k and q_n, for all *k, n*. We observe that (4) can be equivalently studied as a function of $\gamma_{k,n}^{(1)}$ and $\gamma_{k,n}^{(2)}$, or as a function of p_k and q_n, since the two pairs of variables are related by a linear mapping that preserves concavity. We study the concavity of (4) as a function of $\gamma_{k,n}^{(1)}$ and $\gamma_{k,n}^{(2)}$, by computing its Hessian matrix. After some algebra, we obtain (8) shown at the bottom of this page. The diagonal elements of (8) are non-positive, and, thus, it is negative semi-definite if its determinant is non-negative.[4] This is equivalent to:

$$\left(2\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)} - 1\right)\left(\left(\gamma_{k,n}^{(1)}\right)^2 + 2\gamma_{k,n}^{(1)} + \left(\gamma_{k,n}^{(2)}\right)^2 + 2\gamma_{k,n}^{(2)} + 2\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)} + 1\right) \geq 0 \tag{9}$$

from which the proof follows. ■

Remark 1: The condition in Proposition 2 is not very restrictive, since $\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)}$ is the product of the SNRs at the relay and destination, which should not be too low.

B. Users-Relay Association Optimization

If the transmit powers $p_k = \bar{p}_k$ and $q_n = \bar{q}_n$ are fixed for all *k, n*, the optimization with respect to $\{\delta_{k,n}\}_{k,n}$ is:

$$\max_{\{\delta_{k,n}\}_{k,n}} \min_{1\leq k\leq K} \eta_k(\bar{p}_k, \bar{q}_n, \delta_{k,n}) \tag{10a}$$

$$\text{s.t. } \delta_{k,n} \in \{0,1\}, \sum_{n=1}^{N} \delta_{k,n} = 1, \sum_{k=1}^{K} \delta_{k,n} \in \{0,1\}\ \forall k, n. \tag{10b}$$

Since the transmit powers $\{\bar{p}_k\}_{k=1}^K$ and $\{\bar{q}_n\}_{n=1}^N$ are given, one can stack, for any possible relay assignment, the energy efficiencies of all the users in a $K \times N$ matrix $\mathcal{E} = \{\eta_{k,n}\}_{k,n}$, whose elements are $\eta_{k,n} = \frac{B\log_2(1+\gamma_{k,n}(\bar{p}_k,\bar{q}_n))}{\lambda_k\bar{p}_k+\mu_n\bar{q}_n+P_{k,n}^{(c)}}$. The *k*th row gives the energy efficiencies of user *k* if assisted by relay $\{R_n\}_{n=1}^N$, and the *n*th column gives the energy efficiencies of all the users if assisted by Relay R_n. Since a given relay can assist the transmission of only one user, a selection policy is admissible if only one entry of each row is non-zero, and if each of those entries is in a different column. Since the max-min problem in (10) considers individual performance and fairness, an optimal assignment can be obtained by generalizing the algorithms from [4] and [5], to the EE maximization scenario, as explained next.

Step I: The EE matrix $\mathcal{E}$ is computed as explained above. Algorithm 2 is applied to $\mathcal{E}$ to maximize the minimum EE across the users. Let *u* and R_u be the user and the associated relay that achieve the optimum.

[4]Recall that a 2 × 2 Hermitian matrix is non-negative semidefinite if its (1, 1)-element is negative and if its determinant is non-negative.

Algorithm 2 Optimal Relay Assignment for a Given EE Matrix

1: If in Step I, make a random assignment for all users. If in Step II, use the previous selection
2: Set all the relays as "unmarked"
3: Find the smallest EE among the selection. Set the value η_m and relay index k_m
4: Check for a better assignment for the user $\mathcal{U}(R_{k_m})$ using the function `find_another_relay`$(\mathcal{U}(R_{k_m}), k_m, \eta_m)$
5: If a better assignment is found, update the relay assignment accordingly. Otherwise terminate the algorithm.

`find_another_relay`$(\mathcal{U}(R_j), j, \eta_m)$

1: For every "unmarked" relay R_n with $\eta(\mathcal{U}(R_j), R_n) > \eta_m$, do the following in non-increasing order of $\eta(\mathcal{U}(R_j), R_n)$
2: Run the function `check_relay_availability`(R_n, η_m)
3: **if** R_n is available **then**
4: Remove relay R_j from user $\mathcal{U}(R_j)$
5: Assign relay R_n to user $\mathcal{U}(R_j)$
6: **else**
7: Continue on to next R_n and go to line 2
8: **end if**
9: If all relays are unavailable, $\mathcal{U}(R_j)$ cannot find another relay

`check_relay_availability`(R_j, η_m)

1: **if** R_j is not assigned to any user or $R_j = R_{k_m}$ **then**
2: R_j is available.
3: **else**
4: Set R_j as "marked"
5: Run `find_another_relay`$(\mathcal{U}(R_j), R_j, \eta_m)$
6: If $\mathcal{U}(R_j)$ finds another relay, then R_j is available, otherwise it is not
7: **end if**

Step II: After Step I, the *u*-th row and R_u-th column of $\mathcal{E}$ are deleted and Algorithm 2 is applied to the new matrix $\mathcal{E}_u$. This is iterated until all users are associated to a relay.

Both steps use Algorithm 2 to operate on a given EE matrix by the functions[5] `find_another_relay()` and `check_relay_availability()`, where the user associated to relay R_j is denoted by $\mathcal{U}(R_j)$ and its EE by $\eta(\mathcal{U}(R_j), R_j)$.

The computational complexity of the user-relay association procedure can be shown to be quadratic in *K* and *N* [5], whereas the generalized fractional programming to solve (7) requires solving only convex problems [20].

IV. Numerical Results and Discussion

A multi-user and relay-assisted network with $K = N = 10$ is considered. Fast fading is modeled as zero-mean, unit-variance circularly symmetric Gaussian complex random variables, while the channel-to-noise ratios of all the user-relay and relay-destination channels are $u = 10$ and $v = 100$, respectively. Also, $P_{k,n}^{(c)} = 0.1\,\mathrm{W}$ for all *k*, $\mu_n = \lambda_k = 1$ for any

[5]See [4] for further details about these functions.

$$\mathcal{H}_g\left(\gamma_{k,n}^{(1)}, \gamma_{k,n}^{(2)}\right) = \frac{1}{\left(\gamma_{k,n}^{(1)} + \gamma_{k,n}^{(2)} + 1\right)^2}\begin{pmatrix} -\frac{\left(\gamma_{k,n}^{(2)}\right)^2+2\gamma_{k,n}^{(2)}+2\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)}}{\left(\gamma_{k,n}^{(1)}+1\right)^2} & 1 \\ 1 & -\frac{\left(\gamma_{k,n}^{(1)}\right)^2+2\gamma_{k,n}^{(1)}+2\gamma_{k,n}^{(1)}\gamma_{k,n}^{(2)}}{\left(\gamma_{k,n}^{(2)}+1\right)^2} \end{pmatrix} \tag{8}$$

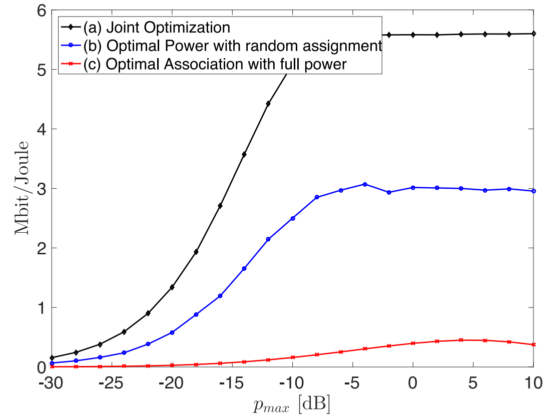

Fig. 2. Minimum EE vs. p_{max} for DF relaying.

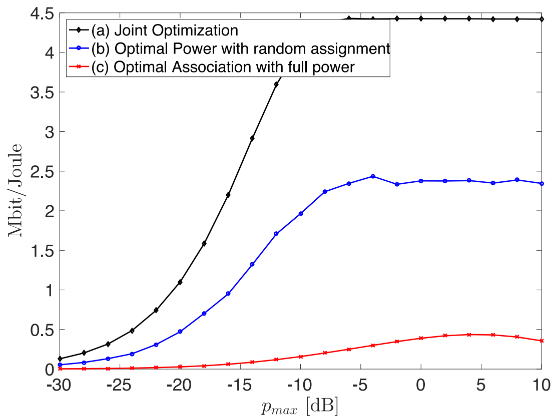

Fig. 3. Minimum EE vs. p_{max} for AF relaying.

TABLE I
ALGORITHM 1. AVERAGE ITERATIONS NUMBER VS. P_{max}

P_{max} [dB]	-30	-20	-10	0	10
No. Iterations for AF	2.82	2.89	3.71	3.85	3.94
No. Iterations for DF	2	2.24	2.95	3.07	3.19

k and n, $B = 1$ MHz, and $q_{max} = 10$ W for all n. Average results over 10^4 system realizations are reported.

Figs. 2 and 3 show the minimum EE in (7a) versus p_{max} (assumed the same for all users), for DF and AF relaying protocols, respectively. The following algorithms are compared: (a) the proposed joint power and relay allocation; (b) optimal power allocation by solving (7), with a random relay assignment; (c) optimal relay assignment by solving (10), with full power transmission. It is seen that the joint allocation of the transmit powers and relay assignment significantly outperforms the optimization of only either the transmit powers or the relay assignments.

Finally, Tab. I shows the average number of outer iterations for Algorithm 1 to converge, versus P_{max}. Convergence is declared when $|\min_k \mathrm{EE}_k^{(n)} - \min_k \mathrm{EE}_k^{(n-1)}|/\min_k \mathrm{EE}_k^{(n)} \leq 10^{-3}$, with $\min_k \mathrm{EE}_k^{(n)}$ denoting the minimum EE achieved in iteration n. The results indicate that convergence occurs in only a few iterations.

V. Conclusion

An algorithm for joint relay assignment and transmit power control has been developed to maximize the minimum among the users' energy efficiencies. The proposed approach merges alternating optimization and fractional programming theory, exhibiting a low complexity, while at the same time improving the EE compared to the optimization of only either the relay assignment or the transmit powers.

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