SCIENCE CHINA
Information Sciences

• LETTER •

February 2018, Vol. 61 029302:1–029302:3
doi: 10.1007/s11432-017-9137-5

Resource allocation in multiple-relay systems exploiting opportunistic energy harvesting

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Received 17 April 2017/Revised 6 June 2017/Accepted 9 June 2017/Published online 13 September 2017

Citation Chen Z Y, Tang L, Zhang X G, et al. Resource allocation in multiple-relay systems exploiting opportunistic energy harvesting. Sci China Inf Sci, 2018, 61(2): 029302, doi: 10.1007/s11432-017-9137-5

Dear editor,

Energy harvesting technique, as an important solution for green communication, has attracted significant concerns from industry and academia. In wireless relay systems, if relays (or destination) are (is) charged by wireless energy, new relaying policies need be developed to satisfy the requirements of information rate and energy transfer efficiency. Refs. [1, 2] investigated how to achieve various tradeoffs by optimizing the transmission schemes for simultaneous wireless information and power transfer in relay systems. Refs. [3,4] concentrated on the performance analysis of relay systems, in which relays harvested energy and forwarded information signals with time switching (TS) or power switching (PS) relaying protocol.

In this article, we study relay networks with one source-destination pair and multiple wireless powered relays in fading channels. All relays replenish energy via opportunistic energy harvesting. Since both the harvested energy and consumed energy of relays depend on time-varying channel state information (CSI), we aim at determining the optimal cooperative transmission and power control scheme to maximize the average throughput of such a system by taking full advantage of fading channels. By assuming the relays always have enough data and energy in storage, the problem is formulated as a convex problem and an upper bound on average throughput is obtained by solving the problem. Based on the optimization results, transmission node selection and transmit power can be determined in a distributed way.

System model and problem formulation. We study a multi-relay system with one source-destination pair, and L wireless powered relays. All relays operate in half duplex mode and DF (decode-and-forward) signals from the source. For simplicity, we only permit the source and relays to transmit in different time slots. The transmission distances in the $\mathcal{S}$-$\mathcal{R}_l$ (source-relay l) link, $\mathcal{S}$-$\mathcal{D}$ (source-destination) link, $\mathcal{R}_l$-$\mathcal{D}$ (relay l-destination) link are denoted as d_{sl}, d_{s0}, d_{rl}, respectively. We assume all of $\mathcal{S}$-$\mathcal{R}_l$, $\mathcal{R}_l$-$\mathcal{D}$ and $\mathcal{S}$-$\mathcal{D}$ channels are Ricean fading channels. The channel gains in the $\mathcal{S}$-$\mathcal{R}_l$ link, $\mathcal{S}$-$\mathcal{D}$ link, $\mathcal{R}_l$-$\mathcal{D}$ link are denoted as $(\gamma_{sl}, \gamma_{s0}, \gamma_{rl})$ and the channel gain vector is written as $\boldsymbol{\gamma} = \{\gamma_{s0}, \gamma_{sl}, \gamma_{rl}, l = 1, \ldots, L\}$. The additive noise power is N_0.

We consider block-based transmission and assume that all links keep constant during each block transmission. During each block time T, the source first spends a fraction of the time $\rho_l(\boldsymbol{\gamma})T$ transmitting to relay l ($1 \leqslant l \leqslant L$) with transmit power $P_{sl}(\boldsymbol{\gamma})$ and transmit rate $r_{sl}(\boldsymbol{\gamma}) = \rho_l(\boldsymbol{\gamma}) \log(1 + \frac{\gamma_{sl} P_{sl}(\boldsymbol{\gamma})}{N_0})$, and spends $\rho_0(\boldsymbol{\gamma})T$ transmitting to the destination with transmit power $P_{s0}(\boldsymbol{\gamma})$ and transmit rate $r_{s0}(\boldsymbol{\gamma}) = \rho_0(\boldsymbol{\gamma}) \log(1 + \frac{\gamma_{s0} P_{s0}(\boldsymbol{\gamma})}{N_0})$. Then the relay l spends $\hat{\rho}_l(\boldsymbol{\gamma})T$ transmitting the re-encoded signals to the destination

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The authors declare that they have no conflict of interest.

with transmit power $P_{rl}(\boldsymbol{\gamma})$ and transmit rate $r_{rl}(\boldsymbol{\gamma}) = \hat{\rho}_l(\boldsymbol{\gamma})\log(1+\frac{\gamma_{rl}P_{rl}(\boldsymbol{\gamma})}{N_0})$. The relay cannot harvest energy when it receives information signals from the source, and it opportunistically harvests wireless energy when the source transmits information signals to the destination or other relays.

Our objective is to optimize transmit parameters $\{P_{sl}(\boldsymbol{\gamma}), P_{rl}(\boldsymbol{\gamma}), \rho_l(\boldsymbol{\gamma}), \hat{\rho}_l(\boldsymbol{\gamma})\}$ to maximize the average throughput, taking into account the total power constraint of the source and energy causality constraints of relays. In the considered channel model, only one node is allowed to transmit in each time slot, i.e.,

$$\sum_{l=0}^{L}\rho_l(\boldsymbol{\gamma}) + \sum_{l=1}^{L}\hat{\rho}_l(\boldsymbol{\gamma}) = 1. \tag{1}$$

The average transmit power at the source is $\bar{P} = \sum_{l=0}^{L}\mathbb{E}_{\boldsymbol{\gamma}}\{\rho_l(\boldsymbol{\gamma})P_{sl}(\boldsymbol{\gamma})\}$, and the average received power at the lth relay is $e_l = \sum_{l'=0,l'\neq l}^{L}\mathbb{E}_{\boldsymbol{\gamma}}\{\rho_{l'}(\boldsymbol{\gamma})\eta\gamma_{sl}P_{sl'}(\boldsymbol{\gamma})\}$ where $0<\eta\leqslant 1$ is the energy conversion efficiency. The average transmit power of the source satisfies

$$\bar{P} \leqslant P_a, \tag{2}$$

where P_a denotes the average power constraint. For each relay, the energy neutrality is achieved by harvesting enough energy from RF signals, i.e.,

$$e_l \geqslant \mathbb{E}_{\boldsymbol{\gamma}}\{\hat{\rho}_l(\boldsymbol{\gamma})P_{rl}(\boldsymbol{\gamma})\}, \quad l=1,\ldots,L. \tag{3}$$

Based on the max-flow-min-cut theorem, the average transmission rate of information bits forwarded by the lth relay should satisfy

$$\bar{r}_l \leqslant \min(\mathbb{E}_{\boldsymbol{\gamma}}\{r_{sl}(\boldsymbol{\gamma})\}, \mathbb{E}_{\boldsymbol{\gamma}}\{r_{dl}(\boldsymbol{\gamma})+r_{rl}(\boldsymbol{\gamma})\}), \tag{4}$$

where $r_{dl}(\boldsymbol{\gamma}) = \rho_l(\boldsymbol{\gamma})\log(1+\frac{\gamma_{s0}P_{sl}(\boldsymbol{\gamma})}{N_0})$.

The message is divided into $L+1$ independent parts: one part is transmitted to the destination via the direct link at a rate $\mathbb{E}_{\boldsymbol{\gamma}}\{r_{s0}(\boldsymbol{\gamma})\}$, and the lth part is decoded and forwarded by the relay l at a rate $\bar{r}_l$. The ergodic capacity $R = \mathbb{E}_{\boldsymbol{\gamma}}\{r_{s0}\} + \sum_{l=1}^{L}\bar{r}_l$.

Then the throughput maximization problem can be formulated as

$$\begin{aligned}\max_{\{P_{sl}(\boldsymbol{\gamma}),\rho_l(\boldsymbol{\gamma}),\hat{\rho}_l(\boldsymbol{\gamma}),P_{rl}(\boldsymbol{\gamma}),\bar{r}_l\}} \quad & \mathbb{E}_{\boldsymbol{\gamma}}\{r_{s0}\} + \sum_{l=1}^{L}\bar{r}_l, \\ \text{s.t.} \quad & (1)\text{–}(4), \quad \{P_{sl}(\boldsymbol{\gamma}), P_{rl}(\boldsymbol{\gamma}), \bar{r}_l\} \geqslant 0, \\ & \{\rho_l(\boldsymbol{\gamma}), \hat{\rho}_l(\boldsymbol{\gamma})\} \in [0,1], \quad \forall l.\end{aligned} \tag{5}$$

If the optimal value of $\bar{r}_l$ equals zero, the lth relay will only harvest energy and not be used to DF information signals.

Optimal solution to (5). We solve (5) utilizing the Lagrange dual method. The problem in (5) can be converted into a convex problem by letting $\tilde{P}_{sl}(\boldsymbol{\gamma}) = \rho_l(\boldsymbol{\gamma})P_{sl}(\boldsymbol{\gamma}), \tilde{P}_{rl}(\boldsymbol{\gamma}) = \hat{\rho}_l(\boldsymbol{\gamma})P_{rl}(\boldsymbol{\gamma})$. The Lagrangian associated with (5) is $\mathcal{L} = \mathbb{E}_{\boldsymbol{\gamma}}\{\mathcal{L}(\boldsymbol{\gamma})\}$, where $\mathcal{L}(\boldsymbol{\gamma}) = r_{s0}(\boldsymbol{\gamma}) + \sum_{l=1}^{L}[(1-\mu_l-\nu_l)\bar{r}_l + \mu_l r_{sl}(\boldsymbol{\gamma}) + \nu_l(r_{dl}(\boldsymbol{\gamma})+r_{rl}(\boldsymbol{\gamma})) - \zeta_l(\tilde{P}_{rl}(\boldsymbol{\gamma}) - \sum_{l'=0,l'\neq l}^{L}\eta\gamma_{sl}\tilde{P}_{sl'}(\boldsymbol{\gamma}))] - \theta\sum_{l=0}^{L}\tilde{P}_{sl}(\boldsymbol{\gamma})$, and $\{\mu_l, \nu_l, \zeta_l, \theta\}$ are Lagrange multipliers. Let $\boldsymbol{\lambda}$ be vector which consists of all multipliers. The dual problem for the problem (5) is given by

$$\min_{\boldsymbol{\lambda}\geqslant 0} g(\boldsymbol{\lambda}), \tag{6}$$

where the dual function is

$$g(\boldsymbol{\lambda}) = \max_{\substack{\{(\tilde{P}_{sl}(\boldsymbol{\gamma}),\tilde{P}_{rl}(\boldsymbol{\gamma}),\bar{r}_l)\geqslant 0,\\ (\rho_l(\boldsymbol{\gamma}),\hat{\rho}_l(\boldsymbol{\gamma})\in[0,1],(1)\}}} \mathbb{E}_{\boldsymbol{\gamma}}\{\mathcal{L}(\boldsymbol{\gamma})\}. \tag{7}$$

The dual problem in (6) can be solved iteratively. Specifically, the optimal values of variables in (7) are obtained by applying the KKT conditions for fixed $\boldsymbol{\lambda}$. Then the solutions of (7) are used for updating $\boldsymbol{\lambda}$ via the sub-gradient method.

We first solve (7) for given $\boldsymbol{\lambda}$. To make the dual function upper bounded, μ_l, ν_l should satisfy $1-\mu_l-\nu_l \leqslant 0$. Then, we have $\max_{\bar{r}_l\geqslant 0}\sum_l(1-\mu_l-\nu_l)\bar{r}_l = 0$. In particular, if $\mu_l+\nu_l>1$, $\bar{r}_l^* = 0$. To compute the optimal transmit powers and time-sharing factors in each fading state, the problem in (7) is decomposed into parallel subproblems with same structure. For a given $\boldsymbol{\gamma}$, the subproblem is expressed as

$$\max_{\substack{\{(\tilde{P}_{sl}(\boldsymbol{\gamma}),\tilde{P}_{rl}(\boldsymbol{\gamma}))\geqslant 0,\\ (\rho_l(\boldsymbol{\gamma}),\hat{\rho}_l(\boldsymbol{\gamma})\in[0,1],(1)\}}} \mathcal{L}(\boldsymbol{\gamma}). \tag{8}$$

The Lagrangian associated with (8) is $\tilde{\mathcal{L}}(\boldsymbol{\gamma}) = \mathcal{L}(\boldsymbol{\gamma}) - \kappa_{\boldsymbol{\gamma}}(\sum_{l=0}^{L}\rho_l(\boldsymbol{\gamma}) + \sum_{l=1}^{L}\hat{\rho}_l(\boldsymbol{\gamma}) - 1)$ where $\kappa_{\boldsymbol{\gamma}}$ is Lagrange multiplier. By letting $\frac{\partial\tilde{\mathcal{L}}(\boldsymbol{\gamma})}{\partial\tilde{P}_{sl}(\boldsymbol{\gamma})} = 0$ and $\frac{\partial\tilde{\mathcal{L}}(\boldsymbol{\gamma})}{\partial\tilde{P}_{rl}(\boldsymbol{\gamma})} = 0$, we can get the optimal solution $P_{sl}^*(\boldsymbol{\gamma}), P_{rl}^*(\boldsymbol{\gamma})$ (see Appendix A). Meanwhile, based on $\frac{\partial\tilde{\mathcal{L}}(\boldsymbol{\gamma})}{\partial\rho_l(\boldsymbol{\gamma})}$ and $\frac{\partial\tilde{\mathcal{L}}(\boldsymbol{\gamma})}{\hat{\rho}_l(\boldsymbol{\gamma})}$, we have the following result.

Lemma 1. Among $\rho_0^*(\boldsymbol{\gamma})$ and $\{\rho_l^*(\boldsymbol{\gamma}), \hat{\rho}_l^*(\boldsymbol{\gamma})\}_{l=1}^{L}$, only the time-sharing factor with maximum partial derivative equals 1 and other factors equal zero.

Proof. See Appendix B.

The optimal solutions in (8) are used for calculating the sub-gradient at $\boldsymbol{\lambda}$ (see Appendix C). As the primal problem is concave, when the optimal dual solution $\boldsymbol{\lambda}^*$ is obtained, the corresponding optimal solutions to (7) must be the primal optimal solutions to problem (5).

Practical transmission scheme. Based on Lemma 1, the general transmission protocol in the "system model" can be simplified as a transmission node selection protocol. Since transmit parameters $\{\rho_l^*(\gamma), P_{sl}^*(\gamma)\}_{l=0}^L$ only depend on CSI $\{\gamma_{sl}\}_{l=0}^L$, and $\{\hat{\rho}_l^*(\gamma), P_{rl}^*(\gamma)\}$ only depend on CSI γ_{rl}, the transmission node selection and power control can be implemented in a distributed fashion. Suppose the source knows $\{\gamma_{sl}\}_{l=0}^L$ and the lth relay knows γ_{rl}. The source and each relay will start their own timer with an initial value $T_0 = \frac{1}{\max_l(\frac{\partial \hat{\mathcal{L}}(\gamma)}{\partial \rho_l(\gamma)})}$ and $T_l = \frac{1}{\frac{\partial \hat{\mathcal{L}}(\gamma)}{\partial \hat{\rho}_l(\gamma)}}$, respectively. The node whose timer reduces to zero first is chosen as the transmit node. The other nodes will overhear the "flag" packet from the transmit node and back off.

The problem in (5) only considers the total energy constraint of each relay. An underlying assumption is relays always have enough data and energy for transmission. In fact, this assumption may not hold since relays replenish energy in an opportunistic and intermittent way. To achieve the energy neutrality of relays, in each block time, the transmission time of each relay need be adapted according to $\boldsymbol{\gamma}$, as well as data and energy in storage [5].

Simulation results. In this section, some numerical results are given to reveal the effect of number of relays on the throughput and verify the tightness of upper bound on throughput in relay systems with different L. The variance of AWGN at the receiver is $N_0 = -80$ dBm. The energy conversion efficiency is $\eta = 0.8$. The small-scale fading of all $\mathcal{S}$-$\mathcal{R}_l$, $\mathcal{R}_l$-$\mathcal{D}$ links obeys $\mathcal{CN}(\frac{1}{\sqrt{2}}, 1)$ distribution. Due to the deep fading, the small-scale fading of $\mathcal{S}$-$\mathcal{D}$ link follows $\mathcal{CN}(\frac{1}{\sqrt{2}}, \alpha)$ distribution where $0 < \alpha < 1$. The path loss in $\mathcal{S}$-R_l, $\mathcal{R}_l$-$\mathcal{D}$, $\mathcal{S}$-$\mathcal{D}$ links are $10^{-2}d_{sl}^{-2}, 10^{-2}d_{rl}^{-2}, 10^{-2}d_{s0}^{-2}$, respectively.

To shorten time for the energy harvesting, all relays are placed near the source or destination. In the network topology in Figure 1, $d_{s0} = 10$ m, $d_{s1} = 9.15$ m, $d_{r1} = 1$ m, $d_{s2} = d_{s3} = \sqrt{2}$ m, $d_{r2} = d_{r3} = \sqrt{82}$ m. When $L = 1$, $\mathcal{R}_1$ is used; when $L = 2$, $\mathcal{R}_1$ and $\mathcal{R}_2$ are used; when $L = 3$, all relays are used. In considered configurations, the achievable rates in the practical scheme approach to the upper bound since relays almost use up energy at the end of the transmission. Generally, the throughput is improved with the increase of L. Meanwhile, it is observed that the throughput improvement from $L = 2$ to $L = 3$ is insignificant. That means the diversity gain coming from small-fading cannot bring great gain in such an energy-constraint system.

Conclusion. This article considers a two-hop system with multiple energy-constrained relays,

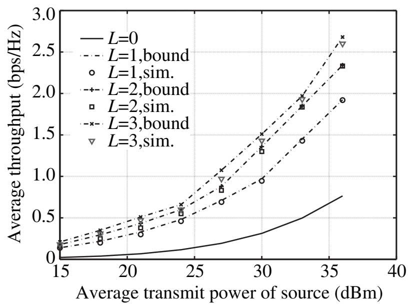

Figure 1 The relationship between average transmission rate and P_a with different L.

where each relay decodes and forwards information signals exploiting the harvested energy. An upper bound on average rate and corresponding closed-form expressions of transmission parameters are obtained by assuming relays always have sufficient data and energy for transmission. Based on optimized results, we propose a feasible transmission scheme which can be implemented in a decentralized way. Simulation results reveal the influence of the number and position of wireless powered relays on the throughput performance.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant No. 61571220) and Open Research Fund of National Mobile Communication Research Laboratory, Southeast University (Grant No. 2015D08).

Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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