

Joint Data and Energy Transmission in a Two-Hop Network With Multiple Relays

Lan Tang, Xinggan Zhang, and Xiaodong Wang, *Fellow, IEEE*

Abstract—Wireless energy transfer (WET) is a promising technique to prolong the lifetime of an energy-constrained wireless network. In this paper, we consider a two-hop communication system with multiple relay nodes powered by WET. To minimize the transmission time, we propose an optimal transmission scheme, in which the relay nodes adopt a “harvest-then-decode and forward” policy. The optimal transmission time allocation of the source and each relay node is calculated by a linear program under causality constraints on both data and energy arrivals. The analytical and simulation results reveal the relationship between the optimal time allocation and system parameters.

Index Terms—Wireless energy transfer (WET), cooperative relay.

I. INTRODUCTION

ENERGY harvesting is a promising technique to prolong the lifetime of an energy-constrained wireless network. In future wireless networks, nodes are envisioned to be capable of harvesting energy from the environment. In addition to the renewable energy resources such as solar and wind, radio signals can be a viable new source due to the emerging wireless energy transfer (WET) technology [1]. In communication systems with WET, energy and information flow simultaneously. Motivated by the characteristics of such systems, the tradeoff between information rate and energy transfer has been investigated in different communication systems, such as MIMO beamforming systems [2], OFDMA systems [3], and AF relay systems [4].

Due to the practical circuit constraints, the receiver is unable to decode the information and harvest the energy from the same signal. Therefore, a “time switching” receiver, which switches its operations periodically between harvesting energy and decoding information, was proposed in [2]. Based on [2], “opportunistic energy harvesting” where the receiver switches between decoding information and harvesting energy based on the channel condition was proposed in [5]. The transmitter using WET can control and optimize the energy provided to the receivers by adjusting the transmission time. [7] studied the sum-throughput maximization of all users by jointly optimizing the time allocation for the downlink wireless power transfer and uplink information transmissions. In [6] and [8], the amplify-and-forward relay network was considered, where an energy-constrained relay harvests wireless energy and uses all harvested energy to forward source signals.

Manuscript received June 24, 2014; accepted September 17, 2014. Date of publication September 25, 2014; date of current version November 7, 2014. This work was supported by the Natural Science Foundation of China (61101082) and the Open Research Fund of the State Key Laboratory of Millimeter Waves (K201514). The associate editor coordinating the review of this paper and approving it for publication was N. Pappas.

L. Tang and X. Zhang are with the Department of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China (e-mail: tanglan@nju.edu.cn; zhxxg@nju.edu.cn).

X. Wang is with the Department of Electrical Engineering, Columbia University, New York, NY 10027 USA (e-mail: wangx@ee.columbia.edu).

Digital Object Identifier 10.1109/LCOMM.2014.2360203

In this paper, we consider a two-hop system with multiple relay nodes powered by WET. We assume that each relay node has no fixed power supply and the source node is the only available RF generator. Similar to [2], we suppose that the relay cannot harvest energy and receive information simultaneously. Therefore, the relay node will replenish energy opportunistically via WET when the source or other relay node transmits. The relay node decodes and forwards the source signal using the harvested energy. Our goal is to determine the optimal transmission scheme which can minimize the transmission time for a given packet. In the proposed transmission scheme, the source node first broadcasts information (or wireless energy) to all relay nodes, and then the relay nodes forward the source signal to the destination using their harvested energy through TDMA. The total transmission time is minimized by jointly optimizing the transmission time of the source node and each relay node given the packet size, based on the channel conditions. The problem is formulated as a linear program. Based on this formulation, we analyze the relationship between time allocation for power transfer and information transmission and system parameters.

II. SYSTEM MODEL AND TRANSMISSION SCHEME

A. System Model

We consider a Gaussian multi-relay channel with one source, one destination, and L relay nodes. A direct link from the source to destination does not exist (e.g., physical obstacles) [6], [8], [9]. So, the information is sent from the source to destination through multiple energy-constrained relay nodes. Channels between the source and relays (or between relays and the destination) are different, but constant during the whole transmission period. The source and the l th relay node use the constant transmit power P_S and $P_l (l=1, \dots, L)$, respectively. When the source transmits to the l th relay node, the transmission rate is $b_{s,l} = \log(1 + \gamma_{s,l} P_S / N_0)$, where $\gamma_{s,l}$ denotes the channel power gain between the source and the l th relay. When the l th relay transmits to the destination, the rate is $b_{l,d} = \log(1 + \gamma_{l,d} P_l / N_0)$, where $\gamma_{l,d}$ denotes the channel power gain between the l th relay and the destination. The relay nodes operate in a half-duplex mode and the source-relay and relay-destination links use the same frequency band. To avoid interference, the source node and relay nodes transmit in different time slots. The relays employ a regenerative, decode-and-forward (DF) strategy.

All relays are assumed to have no fixed power supply and the initial stored energy is zero. The source signal is the only resource of RF radiation and therefore it is used to charge the relay batteries by WET. Due to practical circuit constraints, relay nodes cannot decode the information and harvest energy simultaneously, so the time switching based receiver architecture in [2] is adopted. When one relay receives information from the source, the other relays opportunistically harvest energy from the same signal. The power harvested by the l th relay node can be calculated as $\eta P_s \gamma_{s,l}$, where $0 < \eta \leq 1$ is a

energy conversion efficiency [8]. Furthermore, when one relay transmits, the other relays can also harvest energy from the received RF signals. Specifically, when the l th relay transmits, the power transferred from the l th relay to the l' relay is $\eta P_l \gamma_{l,l'}$, where $\gamma_{l,l'}$ denotes the channel power gain between the l th relay and the l' relay.

We assume that there is a data packet of B bits at the source to be transmitted to the destination. Our objective is to design an optimal transmission scheme to minimize the transmission completion time taking into account the energy and data causality constraints. The key of the transmission scheme is to determine the transmission order and time allocation among the source and relays. Given a transmission order $SR_1 \cdots R_L R_1 \cdots$ (S and R_l denote the source and the l th relay, respectively), the optimal transmission time of each node in each fraction should guarantee the energy and data causality constraints of relays in each fraction.

However, if we do not consider the detailed transmission process, and just consider the energy and data causality of each relay at the end of the transmission, we can obtain a lower bound of the minimal transmission time- J . Actually, whatever the transmission order is, the total transmission time can be decomposed into 1) τ_0 : time assigned to the source node to broadcast wireless energy to all relays; 2) τ_l : time assigned to the source node to transmit data to the l th relay; 3) $T_{E,l}$: total time allocated to the l th relay to broadcast energy to other relays. If the relay has residual energy after finishing data transmission, it can assist other relays' data transmission by transmitting power signals; and 4) $T_{S,l}$: total time allocated to the l th relay to transmit data to the destination. Therefore, the problem of calculating J can be formulated as the following:

$$J = \min_{\tau_0, \tau_l, T_{E,l}} \tau_0 + \sum_{l=1}^L (\tau_l + T_{S,l} + T_{E,l}), \quad (1a)$$

$$s.t. \quad P_l(T_{S,l} + T_{E,l}) \leq \eta \gamma_{s,l} P_s \left(\tau_0 + \sum_{\substack{l'=1 \\ l' \neq l}}^L \tau_{l'} \right) + \sum_{\substack{l'=1 \\ l' \neq l}}^L \eta \gamma_{l',l} P_{l'} (T_{S,l'} + T_{E,l'}), \quad \forall l, \quad (1b)$$

$$b_l T_{S,l} = b_{s,l} \tau_l, \quad \forall l, \quad (1c)$$

$$\sum_{l=1}^L b_{s,l} \tau_l = B, \quad (1d)$$

$$\tau_0 \geq 0, \tau_l \geq 0, T_{E,l} \geq 0, \quad \forall l.$$

The linear constraints in (1b) and (1c) guarantee energy and data causality of each relay at the end of the transmission. That is, for each relay, the total energy consumption should not be more than the harvested energy from the source and other relays, and the total number of transmitted bits should be equal to the total number of received bits.

B. Transmission Scheme

In this section, we will show that the J in (1a) is achievable by constructing a feasible transmission scheme.

To coordinate the data transmission and energy transfer among the nodes, a separate frequency channel is used to broadcast and exchange the signaling. In the proposed transmission scheme, the source transmits first, and then relays forward in the remaining time. At the beginning, the source transmits a

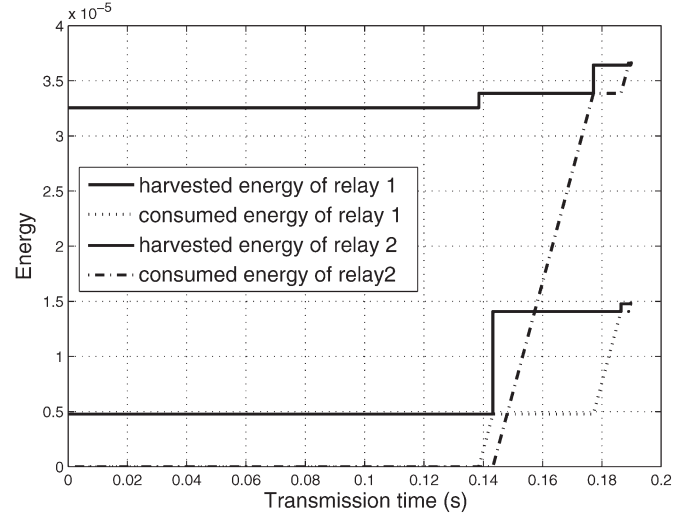


Fig. 1. An example of the proposed scheme ($L = 2$, $P_s = P_l = 1$ mW).

broadcast message which contains the transmission order of relays. Then, the source spends τ_0 to broadcast energy, and τ_l to transmit data to the l th relay ($l = 1, \dots, L$). When one relay receives the data from the source, other relays opportunistically harvest energy. During the period of relay transmission, the relays are to switch between 1) harvesting mode: the relay node harvests energy from RF signals of other relays and 2) relaying mode: the relay node transmits data to the destination or transfers energy to other relays. The relay nodes transmit according to the transmission order. When it is relay l 's turn to transmit, it uses up energy to transmit (if there is residual energy after transmitting data, the relay will transmit power signals). After finishing transmission, relay l broadcasts an "END" signaling so the next relay can switch from the harvesting mode to the relaying mode. The process of relay transmission is repeated until all bits are transmitted to the destination.

In this scheme, relays satisfy the data and energy causality constraints in each transmission. Therefore, we can only consider the data and energy causality constraints at the end of transmission. It is easy to observe that whatever the transmission order is, the problem formulation of minimizing total transmission time is the same as (1). The time allocation in the proposed scheme can be obtained by solving (1). That means J is achievable.

Fig. 1 shows a specific example of the proposed scheme. For a given channel realization, the optimal time allocation ($\tau_0^* = 0.09$, $\tau_1^* = 0.02$, $\tau_2^* = 0.03$) is calculated by (1). The two relays harvest energy and receive data during the time period $[0, 0.14$ s], then transmit to the destination alternatively from 0.14 s to 0.19 s. When one relay transmits, the other relay harvests energy for the next transmission.

III. OPTIMAL TIME ALLOCATION

In this section, we will derive some properties of the optimal solution to (1). For the l th inequality in (1b), we introduce a slack variable ρ_l that represents the remaining energy of the l th relay. We carry out this procedure for each inequality to get the following equivalent representation of (1):

$$J = \min_{\mathbf{x}} \quad \mathbf{c}^T \mathbf{x}, \quad s.t. \quad \mathbf{A} \mathbf{x} = \mathbf{b}, \quad \mathbf{x} \geq 0, \quad (2)$$

where $\mathbf{x} = [\tau_1, \dots, \tau_L, \tau_0, T_{E,1}, \dots, T_{E,L}, \rho_1, \dots, \rho_L]^T$, $\mathbf{c} = [1 + \frac{b_{s,1}}{b_1}, \dots, 1 + \frac{b_{s,L}}{b_L}, 1, 1, \dots, 1, 0, \dots, 0]^T$, $\mathbf{b} = [0, \dots, B]^T$, and

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 & \mathbf{a}_{L \times 1} & \mathbf{A}_2 & \mathbf{I} \\ \mathbf{b}_{1 \times L} & 0 & \mathbf{0}_{1 \times L} & \mathbf{0}_{1 \times L} \end{bmatrix}. \quad (3)$$

In (3), $\mathbf{A}_1$ and $\mathbf{A}_2$ are $L \times L$ matrices, and $\mathbf{I}$ is an $L \times L$ identity matrix. The elements of $\mathbf{A}_1$, $(\mathbf{A}_1)_{i,j} = -\eta(\gamma_{s,i}P_s + \gamma_{j,i}P_j \frac{b_{s,j}}{b_j})$ for $i \neq j$, $(\mathbf{A}_1)_{i,i} = P_i \frac{b_{s,i}}{b_i}$. The elements of $\mathbf{A}_2$, $(\mathbf{A}_2)_{i,j} = -\eta\gamma_{j,i}P_j$ for $i \neq j$, $(\mathbf{A}_2)_{i,i} = P_i$. Furthermore, $(\mathbf{a})_i = -\eta\gamma_{s,i}P_s$, and $(\mathbf{b})_i = b_{s,i}$.

The linear program in (2) can be solved by the simplex method. According to the fundamental theorem of linear program, there exists an optimal solution if the problem is feasible and bounded below. Obviously, $J \geq 0$, so the problem is bounded below. It can be seen that at least one feasible solution exists by considering the simplest case: only one relay is used to DF the signals and other relays just replenish energy.

Suppose $\mathbf{x}^*$ is the optimal solution of (2). Since each relay can transmit data or transfer energy, we denote the relay with $T_{S,l}^* > 0$ as data relay and the relay with $T_{E,l}^* > 0$ as energy relay. The relay can keep harvesting energy from RF signals from other relays, so it may have excess energy at the end of transmission ($\rho_l^* > 0$). We have the following result about the surplus energy and the role of each relay in different systems.

Lemma 1: In the system with $\tau_0^* > 0$, each relay cannot be a data relay and an energy relay simultaneously, and each data/energy relay has no remaining energy when the transmission completes. In the system with $\tau_0^* = 0$, there exist two mutually exclusive cases: one relay is both a data relay and an energy relay, or one data/energy relay has residual energy when the transmission completes.

Proof: According to the property of linear programming, if $\text{Rank}(\mathbf{A}) = L + 1$, there are $L + 1$ nonzero basic variables in the nondegenerate basic feasible solution. On the other hand, for the relay l ($l = 1, \dots, L$), among $(\tau_l^*, T_{E,l}^*, \rho_l^*)$, at least one variable should be greater than zero since each relay must take at least one role: data relay, energy relay or energy harvester. If relay l is used to transmit information, $\tau_l^* > 0$. If relay l is used to transfer energy, $T_{E,l}^* > 0$. Otherwise, the harvested energy will be stored, which makes $\rho_l^* > 0$. Hence, if $\tau_0^* > 0$, among $(\tau_l^*, T_{E,l}^*, \rho_l^*)$, only one variable can be greater than zero. That is, $\tau_l^* T_{E,l}^* = 0$, $\tau_l^* \rho_l^* = 0$, $T_{E,l}^* \rho_l^* = 0$, $\forall l$. If $\tau_0^* = 0$, there exists one relay such that two variables among $(\tau_l, T_{E,l}, \rho_l)$ must be greater than zero. That is, there exists only one relay (say l) which satisfies $\tau_l^* \rho_l^* > 0$ or $\tau_l^* T_{E,l}^* > 0$ or $T_{E,l}^* \rho_l^* > 0$.

In the system with $L = 1$, the source must spend dedicated time to transfer wireless energy to the relay. In the system with multiple relays, when the source or one relay transmits, other relays can opportunistically harvest energy. If the relays can obtain enough energy by opportunistic energy harvesting, the source need not spend dedicated time τ_0 to broadcast wireless energy. Depending on the energy transfer efficiency between the source and relays (or among relays), the system can be categorized as either a low-efficiency or a high-efficiency energy harvesting system. In the low-efficiency energy harvesting system, $\tau_0^* > 0$, which means the source will spend τ_0^* to broadcast energy to all relays. In the high-efficiency energy harvesting system, $\tau_0^* = 0$, which means relay nodes can harvest enough energy during the period of information transmission. Whether a system is a high-efficiency or low-efficiency energy harvesting system depends on the system

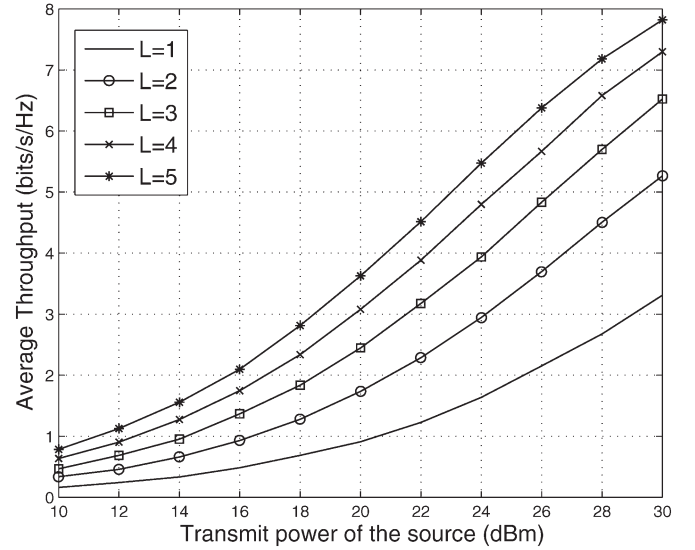


Fig. 2. Average throughput vs. transmit power of the source.

parameters. The following result gives a sufficient condition for a low-efficiency energy harvesting system.

Lemma 2: If $\sum_{j=1, j \neq i}^L \frac{(\mathbf{A}_1)_{i,j}}{(\mathbf{A}_1)_{j,j}} = \eta(\sum_{j=1, j \neq i}^L \gamma_{s,i} \frac{P_s b_j}{P_j b_{s,j}} + \gamma_{j,i}) < 1$, $\forall i$, then, in the optimal solution, $\tau_0^* > 0$.

Proof: We will prove that under the condition of Lemma 2, there is not a feasible solution with $\tau_0 = 0$. The proof is given in the Appendix.

It can be inferred from Lemma 2 that the energy harvesting efficiency of the system is proportional to $L, P_s/P_l, \eta$ and channel gains. In practical systems, $\eta\gamma_{s,i} \ll 1$ and $\eta\gamma_{i,j} \ll 1$. However, by increasing L and P_s/P_l , the energy harvesting efficiency can be improved.

IV. SIMULATION RESULTS

We employ the average throughput to evaluate the performance of different system configurations. Based on the minimal transmission time J , the throughput is given by B/J . The average throughput is obtained by 10^5 Monte Carlo simulations. The bandwidth is set to 10 MHz. The channel power gains are modeled as an exponentially distributed random variable multiplied with a κ th-power path loss ($\kappa = 2$). The AWGN at the receiver is assumed to have a white power spectral density of -170 dBm/Hz. The energy harvesting efficiency is assumed to be $\eta = 0.7$. The distance between the source and the destination is 6 m. In each channel realization, positions of relay are generated randomly in a 6×6 square.

Fig. 2 shows the average throughput versus P_s for different number of relays L . $P_l = 1$ mW. As implied in Lemma 2, when P_s/P_l and L are small, relay nodes cannot obtain enough energy by opportunistic energy harvesting. For example, when $L = 2$, $P_s = 10$ mW, the probability that $\tau_0^* = 0$ is less than 10^{-4} . When $L = 5$ and $P_s = 1$ W, the probability that $\tau_0^* = 0$ is greater than 65%. Therefore, increasing P_s or L helps to improve the energy transferring efficiency and increase the probability that $\tau_0^* = 0$. Next, by fixing $P_s = 100$ mW, Fig. 3 illustrates the average throughput over P_l for different L . The total transmission time includes the energy harvesting time and the data transmission/reception time of all relays. Increasing P_l will improve the transmission rate of the relay node, meanwhile, prolong the energy harvesting time. From Fig. 3, we can get the optimum P_l to achieve the maximum throughput. Fig. 4

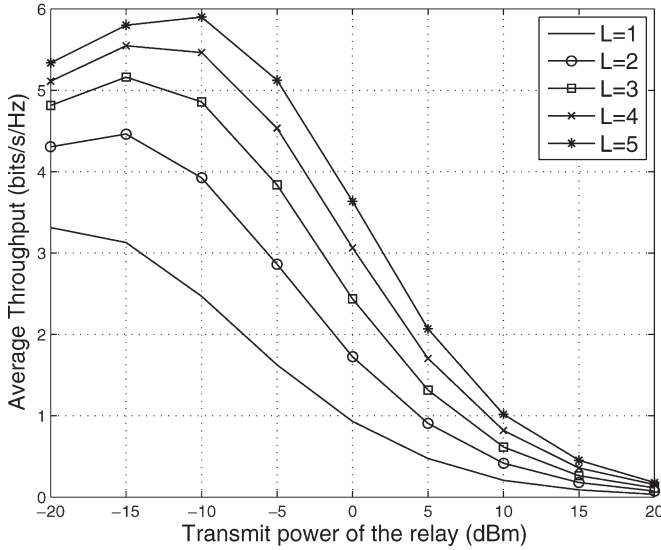
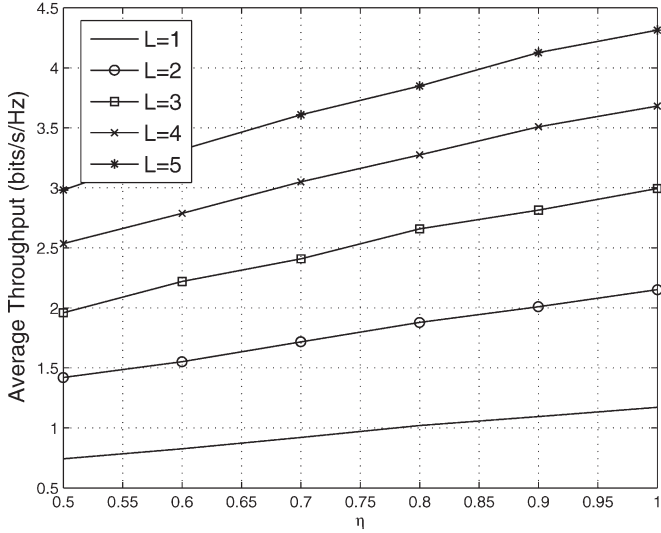


Fig. 3. Average throughput vs. transmit power of the relay.

Fig. 4. Average throughput vs. η ($P_s = 100$ mw, $P_l = 1$ mw).

displays the relationship between the average throughput and η . Obviously, increasing η can improve the throughput.

V. CONCLUSION

This letter considers a two-hop communication system where relay nodes harvest energy from transmitted RF signals. Assuming each relay can harvest energy opportunistically when the source or other relay transmits, we have proposed an optimal transmission scheme which can achieve the maximum transmission rate. The optimal time allocation can be obtained by solving a linear program. Through analytical and simulation results, we have revealed the relationship between the energy harvesting efficiency and system parameters.

APPENDIX

We use the proof by contradiction to prove Lemma 2. Assuming that in the optimal solution, $\tau_0^* = 0$. According to Lemma 1, there exists only one relay (say l) which satisfies $\tau_l^* \rho_l^* > 0$ or $\tau_l^* T_{E,l}^* > 0$ or $T_{E,l}^* \rho_l^* > 0$. However, we will show that under the conditions of Lemma 1, we cannot find such a relay l .

Assume that $\mathbf{x}$ is a feasible solution of (2), $\mathbf{B}$ consists of $L + 1$ linear independent column vectors from $\mathbf{A}$ in (3), and $\mathbf{x} = [(\mathbf{B}^{-1}\mathbf{b})^T, 0]^T = [B\mathbf{c}^T, 0]^T$. $\mathbf{c}$ is the last column of $\mathbf{B}^{-1}$. Without loss of generality, we suppose that τ_1 and ρ_1 are nonzero basic variables in $\mathbf{x}$. So, $\mathbf{B}$ can be written as

$$\mathbf{B} = \begin{bmatrix} \mathbf{X} & \mathbf{e} \\ \tilde{\mathbf{b}} & 0 \end{bmatrix} \quad (4)$$

where $\tilde{\mathbf{b}} > 0$, $\mathbf{e} = [1, 0, \dots, 0]^T$ and each column of $\mathbf{X}$ comes from $\mathbf{A}_1$ or $\mathbf{A}_2$ or $\mathbf{I}$. According to the proof of Lemma 1, each column of $\mathbf{X}$ corresponds to a different relay node. To finish the proof, we need the following result.

Lemma 3: $\mathbf{X}^{-1}$ is a positive matrix.

Proof: By interchanging rows of $\mathbf{X}$, we can make $X_{i,i} > 0$ and $X_{i,j} \leq 0$. Set $\mathbf{\Lambda} = \text{diag}(\mathbf{X})$ and $\mathbf{B} = \mathbf{I} - \mathbf{X}\mathbf{\Lambda}^{-1}$. The matrix $\mathbf{B}$ has all 0's on the main diagonal, and $B_{i,j} = -X_{i,j}/X_{j,j} > 0$ if $i \neq j$. The condition in Lemma 3 guarantees that $\sum_{j=1, j \neq i}^L \frac{|X_{i,j}|}{X_{j,j}} \leq \sum_{j=1, j \neq i}^L \frac{|(\mathbf{A}_1)_{i,j}|}{(\mathbf{A}_1)_{j,j}} < 1$. So, the spectral radius of $\mathbf{B}$ $\rho(\mathbf{B}) < \|\mathbf{B}\|_\infty < 1$. When $\rho(\mathbf{B}) < 1$, by Taylor series expansion, $(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{I} + \sum_{n=1}^{\infty} \mathbf{B}^n$. As a result, $\mathbf{X}^{-1} = \mathbf{\Lambda}^{-1}(\mathbf{I} + \sum_{n=1}^{\infty} \mathbf{B}^n)$. Since both $\mathbf{B}$ and $\mathbf{\Lambda}$ are positive, $\mathbf{X}^{-1}$ is a positive matrix.

Based on the formula of inverse matrix, $\mathbf{c}$ can be written as

$$\mathbf{c} = \begin{bmatrix} \mathbf{X}^{-1}\mathbf{e}/(\tilde{\mathbf{b}}\mathbf{X}^{-1}\mathbf{e}) \\ -1/(\tilde{\mathbf{b}}\mathbf{X}^{-1}\mathbf{e}) \end{bmatrix}. \quad (5)$$

Due to $\mathbf{X}^{-1} > 0$, we have $\rho_1 = (\mathbf{x})_{L+1} = B(\mathbf{c})_{L+1} < 0$. Similarly, we can prove that if $T_{E,1} > 0$, $\rho_1 < 0$.

Finally, we suppose that τ_1 and $T_{E,1}$ are nonzero basic variable in $\mathbf{x}$. In this case, $\mathbf{e}$ in (5) becomes the first column of $\mathbf{A}_2$. According to the proof of Lemma 3, $\mathbf{X}^{-1}\mathbf{e}$ can be written as $\mathbf{\Lambda}^{-1}(\mathbf{I} + \sum_{n=1}^{\infty} \mathbf{B}^n)\mathbf{e}$. It is easy to calculate that the first element of $\mathbf{X}^{-1}\mathbf{e}$ must be greater than zero. So, if $T_{E,1} = B\mathbf{c}_{L+1} > 0$, $\tau_1 = B\mathbf{c}_1 < 0$.

In summary, the condition in Lemma 2 guarantees that when $\tau_0 = 0$, we cannot find a feasible solution.

REFERENCES

- [1] R. Want, "An introduction to RFID technology," *IEEE Pervasive Comput.*, vol. 5, no. 1, pp. 25–33, Jan.–Mar. 2006.
- [2] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.
- [3] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer in multiuser OFDM systems," in *Proc. IEEE GLOBECOM*, pp. 4092–4097.
- [4] B. K. Chalise, W.-K. Ma, Y. D. Zhang, H. A. Suraweera, and M. G. Amin, "Optimum performance boundaries of OSTBC based AF-MIMO relay system with energy harvesting receiver," *IEEE Trans. Signal Process.*, vol. 61, no. 17, pp. 4199–4214, Sep. 2013.
- [5] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 2, no. 1, pp. 288–300, Jan. 2013.
- [6] I. Krikidis, S. Timotheou, and S. Sasaki, "Energy transfer for cooperative networks: Date relaying or energy harvesting?" *IEEE Commun. Lett.*, vol. 16, no. 11, pp. 1772–1775, Nov. 2012.
- [7] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–429, Jan. 2014.
- [8] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3637, Jul. 2013.
- [9] R. Tannous and A. Nosratinia, "Spectrally-efficient relay selection with limited feedback," *IEEE J. Areas Sel. Commun.*, vol. 26, no. 8, pp. 1419–1428, Oct. 2008.