Contract Theory Based on Wireless Energy Harvesting with Transmission Performance Optimization

Chen Liu(✉), Hong Peng, Weidang Lu, Zhijiang Xu, and Jingyu Hua

College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, People's Republic of China
1078017312@qq.com, {ph,luweid,zyfxzj,eehjy}@zjut.edu.cn

Abstract. In this paper, we proposed a contract theory on optimization of wireless energy collection and transmission systems. Its purpose is to maximize the transmission rate of the source node to the destination node. Source node broadcasts signal to relay node. We assume that the quality of the link between the source node and the destination node link is poor, and the signal cannot be directly transmitted to the destination node. Relay node have no energy to forward the signal. At this time, the relay node needs energy from surrounding energy access points (EAPs) and the destination node will pay corresponding rewards. We designed the optimal contract theory in order to maximize the transmission performance of the source node. Finally, we use the optimal algorithm to get the best result.

Keywords: Contract theory · Wireless Energy Harvesting · Optimal algorithm Performance optimization

1 Introduction

Wireless Energy Harvesting has been a lot of research. In the literature [1], An IOT system based on radio frequency energy collection is considered, which consists of a data access point (DAP) and multiple energy access points (EAP). Compare stackelberg game and optimal contract with symmetric and asymmetric information respectively. Contract Theory is also used in many scientific researches. A contract-theory based framework under asymmetric and symmetric channel information is proposed in [2], and introduced the cooperation between the primary user and the secondary user. And system performance can be improved by obtaining diversity gain in cooperative communication [3]. While there are several initial work designing the incentive mechanism [4–6] for the EAPs belonging to different operators, complete information was considered in these schemes. In [7, 8], Amplify-and-forward (AF) and decode-and-forward (DF) protocol transmission methods are also studied. In order to maximize throughput in wireless powered communication networks, which paper use convex optimization and get the optimal solution in [9, 10].

In this paper, we discuss that the relay node amplifies and forwards information to the destination node through the AF protocol.

L. Meng and Y. Zhang (Eds.): MLICOM 2018, LNICST 251, pp. 400–408, 2018.
https://doi.org/10.1007/978-3-030-00557-3_40

We assume that the relay node has no energy and only one EAP around it provides energy to the relay node to help it forward information. The structure of this article is as follows. Section 2 introduces the system model and formulates the optimization problem of the model. Section 3 we give the optimal solution to the optimization problem. Computer simulation results are displayed in Sects. 4 and 5 we finally make conclusions for this paper.

2 System Model and Problem Formulation

2.1 System Model

We suppose source node to the destination node link experiences a poor link quality. Source node needs the relay node to help forward its information to the destination node using the AF protocol, but the destination node has no energy to forward signal. In this case, it needs to obtain energy from the EAP and forward the information with the acquired energy and EAP get the profit by the backhaul. The model is shown in Fig. 1.

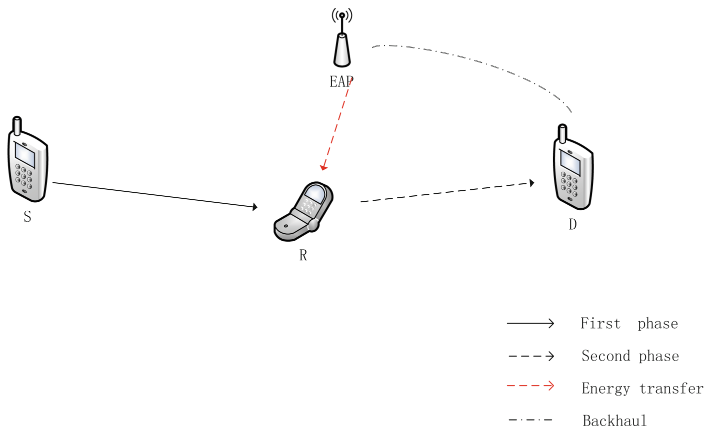

Fig. 1. System model

In the first phase, source node sends signal to the relay node, and surrounding EAP send the energy to the relay node. The energy harvested by the relay node can be expressed as

$$E_R = \eta p_E G_{E,R} \tag{1}$$

Where p_E denotes the charging power of the EAP and $G_{E,R}$ denotes the channel power gain between the EAP and the relay node.

The energy obtained by the relay is used to transmit information to the destination node in the second time slot. We assume that the relay node use all the energy to forward the message. The transmit power of the relay node is thus given by

$$E_R = P_R \tag{2}$$

The system uses AF protocol to forward information. The signal received by the relay node is denoted as

$$y_R = \sqrt{P_{SR}} h_{S,R} x_1 + n_1 \tag{3}$$

The relay node amplifies the signal and forwards it to the destination node, which is expressed as

$$y_D = \Phi y_R h_{R,D} + n_2 \tag{4}$$

Where P_{SR} is the transmit power of source node, $h_{S,R}$ is the channel gain between the source node and the relay node, ϕ is a magnification factor, X_1 is the signal that sent by the source node, n_1 and n_2 is the noise power, $h_{R,D}$ is the channel gain from the relay node to the destination node.

Therefore, the SNR of destination node is expressed as:

$$\begin{aligned} SNR &= \frac{\frac{p_{SR}|h_{S,R}|^2}{\sigma^2} \cdot \frac{\eta p_E G_{E,R} |h_{R,D}|^2}{\sigma^2}}{1 + \frac{p_{SR}|h_{S,R}|^2}{\sigma^2} + \frac{\eta p_E G_{E,R} |h_{R,D}|^2}{\sigma^2}} \\ &= \frac{\eta p_{SR} |h_{S,R}|^2 |h_{R,D}|^2 p_E G_{E,R}}{\sigma^4 + \sigma^2 p_{SR} |h_{S,R}|^2 + \eta \sigma^2 |h_{R,D}|^2 p_E G_{E,R}} \end{aligned} \tag{5}$$

Hence the achievable throughput (bps) from the relay node to the destination node can be expressed

$$\begin{aligned} R_{R,D} &= \frac{1}{2}\log_2(1 + SNR) \\ &= \frac{1}{2}\log_2(1 + \frac{\eta p_{SR} |h_{S,R}|^2 |h_{R,D}|^2 p_E G_{E,R}}{\sigma^4 + \sigma^2 p_{SR} |h_{S,R}|^2 + \eta \sigma^2 |h_{R,D}|^2 p_E G_{E,R}}) \end{aligned} \tag{6}$$

In order to facilitate the calculation, we make the following substitutions.

$$q_R = p_E G_{E,R} \tag{7}$$

$$a = \eta p_{SR} |h_{S,R}|^2 |h_{R,D}|^2 \tag{8}$$

$$b = \sigma^4 + \sigma^2 p_{SR} |h_{S,R}|^2 \tag{9}$$

$$c = \eta\sigma^2|h_{R,D}|^2 \tag{10}$$

Therefore,

$$R_{R,D} = \frac{1}{2}log_2\left(1 + \frac{\mathrm{a}q_R}{\mathrm{b} + \mathrm{c}q_R}\right) \tag{11}$$

Where q_R is the received signal power at the relay node from the EAP.

We assume that π_E is the gain of EAP. The utility function of the destination node can be defined as

$$U_D(\pi_E, q_R) = R_{R,D} - \pi_E \tag{12}$$

The utility of EAP is defined as

$$U_E(\pi_E, q_R) = \pi_E - C_k(p_E) \tag{13}$$

Where $C_k(\mathrm{x})$ is used to model the energy cost of the EAP, given by

$$C_k(\mathrm{x}) = a_E x^2 \tag{14}$$

Where a_E is the energy cost coefficient. The utility function of the EAP becomes

$$U_E(\pi_E, q_R) = \pi_E - \frac{a_E}{G_{E,R}^2}q_R^2 \tag{15}$$

We define the type of the EAP as

$$\theta = \frac{G_{E,R}^2}{a_E} \tag{16}$$

$$U_E(\pi_E, q_R) = \pi_E - \frac{q_R^2}{\theta} \tag{17}$$

The utility of the destination node with EAP is given by

$$U_D(\pi_E, q_R) = \frac{1}{2}log_2\left(1 + \frac{\mathrm{a}q_R}{\mathrm{b} + \mathrm{c}q_R}\right) - \pi_E \tag{18}$$

2.2 Problem Formulation

Definition 1 (Individual Rationality, IR). The contract satisfies the IR constraint that the EAP obtains a nonnegative payoff when it provides power for the relay, i.e.

$$U_E(\pi_E, q_R) = \pi_E - \frac{q_R^2}{\theta} \geq 0 \tag{19}$$

Following the idea of contract theory, the goal of the source node is to maximize the use of IR constraints. Therefore, the optimization problem can be solved using the optimal contract.

$$\mathbf{P1:} \qquad \max\{U_D(\pi_E, q_R)\} \tag{20}$$

$$\mathbf{s.t} \qquad \pi_E - \frac{q_R^2}{\theta} \geq 0 \tag{21}$$

$$q_R \geq 0, \pi_E \geq 0, \theta \geq 0 \tag{22}$$

3 Optimal Solution

The optimal contract is designed to maximize transmission efficiency of the source node to the destination node utility. We first realize that the following necessary conditions can be derived from the IR constraints.

Lemma 1. In an optimal contract, the EAP obtains zero payoff by accepting the corresponding contract item, the optimal prices are given by

$$\pi_E^* = \frac{q_R^2}{\theta} \tag{23}$$

Proof. Since the optimization objective function is an increasing function of q_R and a decreasing function of π_E. When they are equal, it can be achieved maximum utility of transmission efficiency of the source node to the destination node. So we completed the proof.

We substitute π_E with π_E^* and get

$$\mathbf{P2:} \qquad \max\{U_D(\pi_E^*, q_R)\} \tag{24}$$

$$\mathbf{s.t} \qquad q_R \geq 0, \pi_E \geq 0, \theta \geq 0 \tag{25}$$

Then put (18) and (23) into this formula, we get

$$U_D(\pi_E, q_R) = \frac{1}{2}log_2\left(1 + \frac{aq_R}{b + cq_R}\right) - \frac{q_R^2}{\theta} \tag{26}$$

Take the first derivation of U_D with regard to q_R, then, the optimal solution can be obtained when the first derivation of U_D equals to zero. Thus, we can obtain:

$$\frac{1}{2}\frac{\left[\frac{a(b+cq_R)-aq_Rc}{(b+cq_R)^2}\right]}{(1+\frac{aq_R}{b+cq_R})\ln 2}-\frac{2q_R}{\theta}=0 \tag{27}$$

$$q_R=\frac{\sqrt{a^2b^2\ \ln^2 2+2a^2bc\theta\ \ln 2+2abc^2\theta\ \ln 2}-ab\ \ln 2-2bc\ \ln 2}{2(ac\ \ln 2+c^2\ln 2)} \tag{28}$$

$$\pi_E^*=\frac{q_R^2}{\theta} \tag{29}$$

So we can get the optimal solution from the above.

4 Simulation Results

In this section, we draw the graph of the maximum utility function based on the optimal solution found above. Without loss of generality, we assume that the noise for all the links is white Gaussian noise. Considering a cooperative system which is composed one source node, one relay node and destination node and one EAP that provides energy. So, we set a few different parameters and compare them and see how the graph changes from the simulation. We can draw some conclusions through the simulation chart.

Figure 2 shows the distance from the relay node to the destination node influences the value of the utility function. We can observe that the further the distance from the relay node to the destination node, the smaller the value of the transmission utility will be. It is because of the distance increasing, the channel quality will become worse. In the upper right corner of the figure, η stands for the energy harvesting efficiency. We can also see from the figure that the higher the energy harvesting efficiency, the more energy the relay node receives, therefore, the larger the value of the transmission utility function.

Figure 3 shows the relationship between the value of the utility function and the energy cost coefficient. As the energy cost coefficient gradually increases, the value of the utility function rises first to reach a peak and then begins to decline. Because of the contract theory that they have reached, EAP with the exchange of energy to get the benefits, when reaching a certain value, the utility function will be the best. After this point, the value of the utility function will begin to decrease as the energy cost coefficient decreases. Due to the higher the energy cost coefficient, the greater the payoff will be given by destination node. And it can also be observed that as the noise variance gradually increase, the value of the utility function decreases gradually, because the channel gain is getting worse.

From the Fig. 4, we can observe that accompanied by p_{SR} gradual increase, U_D first rises quickly then slowly, finally tends to be stable. We can observe that transmit power also affects the value of the utility function. From the figure, we can also see that if the energy cost coefficient becomes larger, the value of the utility function will also decrease. This is also because with the energy cost coefficient increases, EAP revenue will increase, lead to transmission utility will also be reduced.

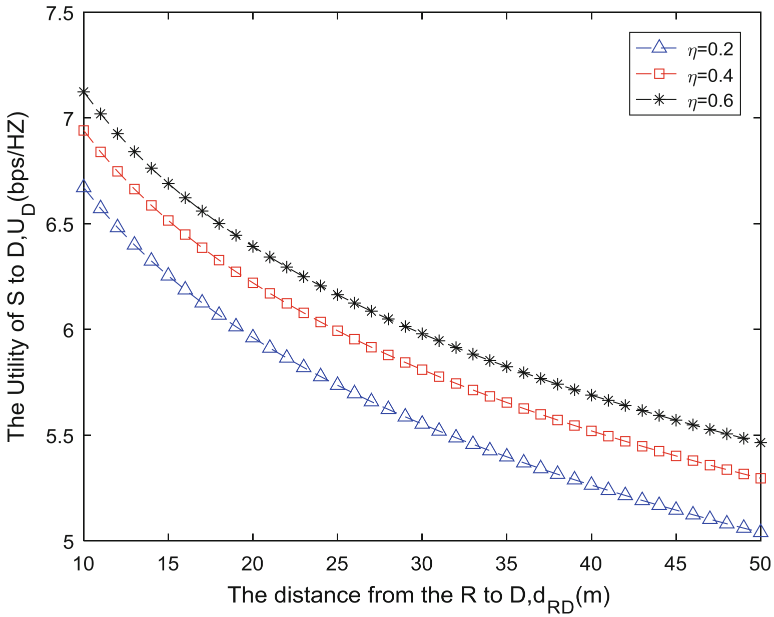

Fig. 2. The relationship between the distance from R to D and the utility function value

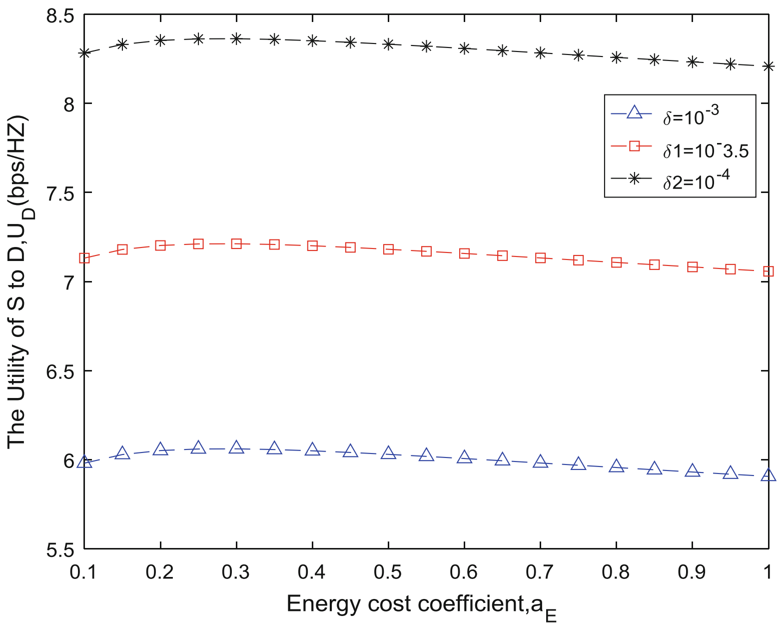

Fig. 3. The relationship between the energy cost coefficient and the utility function value

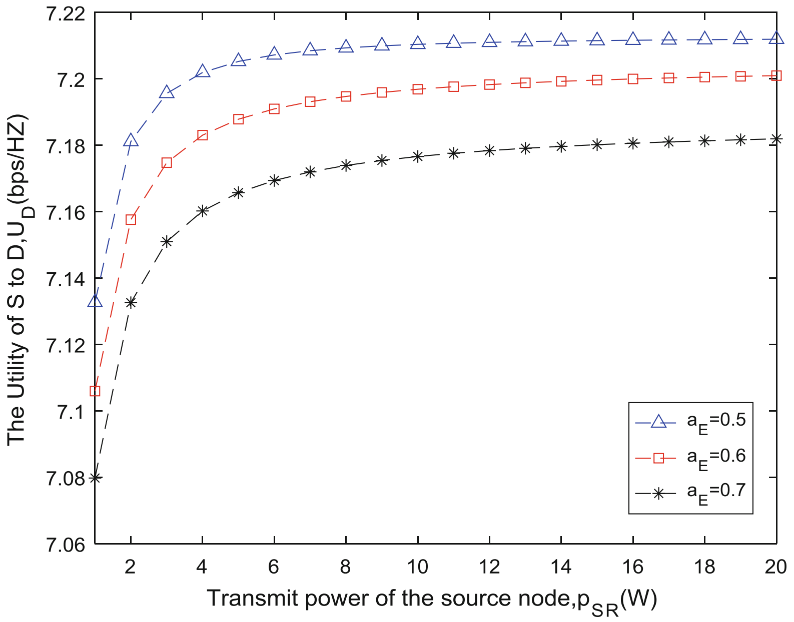

Fig. 4. The relationship between transmit power of the S node and the utility function value

5 Conclusion

In this paper, we proposed a contract theory based on Wireless Energy Harvesting in order to maximize the transfer efficiency of source node. We also use the IR constraint to simplify the target formula. Finally, we use the convex optimization algorithm to obtain the optimal solution. In the model, we use contract theory to hire surrounding EAPs to provide energy to help forward information. For convenience, we suppose only one EAP participate in the contract theory to provide energy. The final simulation shows that there are still many factors that affect transfer efficiency.

References

1. Hou, Z., Chen, H., Li, Y., Vucetic, B.: Incentive mechanism design for wireless energy harvesting-based Internet of Things. IEEE Internet Things J. (2017). https://doi.org/10.1109/JIOT
2. Lu, W., He, C., Lin, Y.: Contract theory based cooperative spectrum sharing with joint power and bandwidth optimization. Project funded by China Postdoctoral Science Foundation under Grand No. 2017M612027
3. Liu, J., Ding, H., Cai, Y., Yue, H., Fang, Y., Chen, S.: An energy-efficient strategy for secondary users in cooperative cognitive radio networks for green communications. IEEE J. Sel. Areas Commun. **34**(12), 3195–3207 (2016)

4. Chen, H., Li, Y., Han, Z., Vucetic, B.: A stackelberg game-based energy trading scheme for power beacon-assisted wireless-powered communication. In: Proceedings of ICASSP, pp. 3177–3181, April 2015
5. Sarma, S., Kandhway, K., Kuri, J.: Robust energy harvesting based on a Stackelberg game. IEEE Wirel. Commun. Lett. **5**(3), 336–339 (2016)
6. Ma, Y., Chen, H., Lin, Z., Li, Y., Vucetic, B.: Distributed and optimal resource allocation for power beacon-assisted wireless-powered communications. IEEE Trans. Commun. **63**(10), 3569–3583 (2015)
7. Li, Y., Wang, W., Kong, J., Peng, M.: Subcarrier pairing for amplify-and-forward and decode-and-forward OFDM relay links. IEEE Commun. Lett. **13**(4), 209–211 (2009)
8. Zhong, C., Suraweera, H., Zheng, G., Krikidis, I., Zhang, Z.: Wireless information and power transfer with full duplex relaying. IEEE Trans. Commun. **62**(10), 3447–3461 (2014)
9. Ju, H., Zhang, R.: Throughput maximization in wireless powered communication networks. IEEE Trans. Wirel. Commun. **13**(1), 418–428 (2014)
10. Boyd, S., Vandenberghe, L.: Convex Optimization. Cambridge University Press, Cambridge (2004)