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On the energy efficiency of relay selection in multi-relay cooperative network using Vickrey auction game①

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Abstract

This paper focuses on the energy efficient relay selection problem in a cooperative multi-relay network, aims to find the most energy efficient relay node for the source node while ensuring its minimum data rate requirement. The interaction between the source node and the relay nodes is modeled as a Vickrey auction game, when the source node broadcasts a cooperation request, the relay nodes compete for the cooperation, and the one with the minimum bid will be chosen which denotes the cost of the source node during the cooperation process, but it only needs to provide the minimum bid provided by the other relay nodes, which can encourage all the relay nodes to give the true bid. Besides, the minimum rate requirement of the source node will be ensured and the relay node taking part in the cooperation will gain some reward and the reward can be maximized by reinforcement learning (RL).

Key words: relay selection, energy efficient, Vickrey auction game

0 Introduction

Collaborative communication is seen to have a good prospect in mobile communication system of the next generation. The basic idea of collaborative communication is that users of single antennas can utilize antennas of partnerships to form a virtual antenna array with the broadcasting nature of wireless channels, which can obtain the spatial diversity[1]. On the other hand, with the rapid growth of intelligent devices, more and more people use them to connect the internet, therefore both the devices and the BS (base station) need to deal with amounts of information, and not only the BS but also the mobile devices consume lots of energy, which makes the energy efficiency a critical problem to be solved[2].

In a multi-relay cooperative wireless network, energy efficiency is also an important performance indicators mainly considered. In Ref. [3], expressions are obtained for the total energy consumption for general relay selection and outage criteria for the non-homogeneous case in which different relay links have different mean channel power gains. In Ref. [4], the best destination node based on the channel quality of the direct links is selected first and then the best relay is selected to yield the best path from the source to the selected destination which can also save the consumed energy. But both the above papers assume that the relay nodes are altruistic and willing to help the source node unconditionally, ignoring the relay node's own benefit, however, the relay nodes are selfish and need to be stimulated, so an incentive scheme based on the game theory is studied.

In Ref. [5], the author considers the effect of selfishness on energy efficiency using a non-cooperative game theoretic approach, a two-source relaying game is formulated for both non-fading and fading scenarios. In Ref. [6], the author presents a business model to trade power between a single source node and several relay nodes considering procurement auction based game theoretic model using a first price auction. But either the pricing game or the first price auction considers the actual bid given by bidders to the auctioneer while ignoring the bidder's concern that the auction items aren't worthy of their bids and they will reduce their bids in a practical auction.

To encourage the bidders to give their actual bids in an auction and get a real evaluation of one item, Vickrey auction game is proposed. In a Vickrey auction, all the bidders send their bids to the auctioneers

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to win a bid, the one with the highest bid will win the auction, but the actual price it finally pays is the highest bid that the failing bidders provide, which makes each bidder consider its own bid only and needn't to pay attention to other bidder's bid which could simplify the bid process.

Based on Vickrey auction game, we propose an energy efficient relay node selection scheme in this paper. When the source node broadcasts a cooperation request, the relay node with the bid to make the cooperation most energy efficient is selected, but it just only needs to provide the minimum bid that the residual relay nodes provide in the end. In addition, the selected relay node can also get reward from the cooperation and the award can be maximized by reinforcement learning (RL)[6].

1 System model

1.1 Network model

The network model is shown in Fig. 1, in which there are one source node S, one destination node D and N relay nodes. We adopt the amplify-and-forward (AF) cooperation protocol here. The cooperative transmission process consists of two phases: in phase 1, S broadcasts its information to both destination node D and each relay node r_i while in phase 2, relay node r_i amplifies the received signal and forwards it to destination node D with transmitted power P_{r_i}. The two phases are illustrated as Fig. 2.

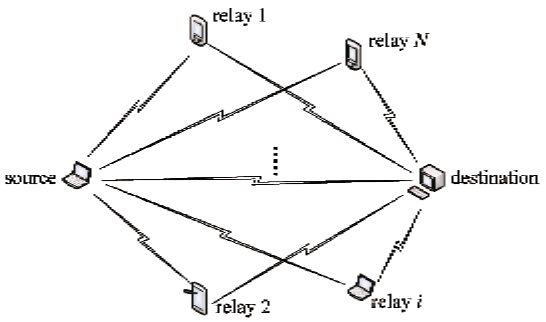

Fig. 1 System diagram

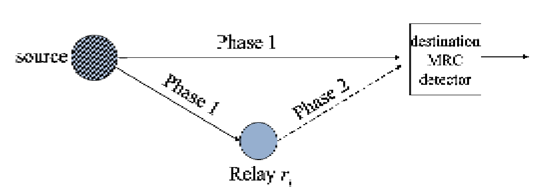

Fig. 2 The cooperation transmission process

Denote the channel gain from S to D, S to r_i and r_i to D as $g_{s,d}$, g_{s,r_i} and $g_{r_i,d}$ respectively, we can get the SNR that results from the direct transmission from the source node S to the destination node D, expressed as

$$\Gamma_{s,d} = P_s g_{s,d} / \sigma^2 \tag{1}$$

where P_s represents the transmit power at node S, σ^2 denotes the noise power and considered to be the same for all the links.

And the rate of the direct transmission is

$$R_{s,d} = W \log_2 (1 + \frac{\Gamma_{s,d}}{\Gamma}) \tag{2}$$

where W is the transmission bandwidth, Γ is a constant representing the capacity gap.

The SNR of S with relay node r_i for help in phase 2 is

$$\Gamma_{s,r_i,d} = \frac{P_s P_{r_i} g_{r_i,d} g_{s,r_i}}{\sigma^2 (P_{r_i} g_{r_i,d} + P_s g_{s,r_i} + \sigma^2)} \tag{3}$$

By Eqs(1) and (3), the rate at the output of the maximal ratio combining (MRC) detector with the help of relay node r_i is got as

$$R_{s,r_i,d} = W \log_2 (1 + \frac{\Gamma_{s,d} + \Gamma_{s,r_i,d}}{\Gamma}) \tag{4}$$

1.2 Energy efficiency performance criteria

In Ref. [7], the energy efficiency performance criterion is defined to take the power consumption cost into account during transmissions, and the utility function can be written as

$$\eta = W \log_2 (1 + \frac{h^2 P}{\sigma^2}) - uP \tag{5}$$

where W is the transmission bandwidth, h and P are the channel gain and power allocation respectively. σ^2 is additive Gaussian white noise with zero mean and unit variation and u is a price parameter with the unit of bit/s/W.

2 Problem formulation

Before the problem formulation, the definition of Vickrey auction is given at first[8]. In an auction with K objects for sale and N bidders, bidder i's valuation of the objects is $\mathbf{X}^i = (X_1^i, X_2^i, \cdots, X_K^i)$, where X_k^i represents the value of bidder i to obtain the kth object. Then for the kth object, there are N bids, denoted as $X^k = (X_1^k, X_2^k, \cdots, X_K^k)$, this auction is called the Vickrey auction if: (1) For the kth object, the highest bid X_i^k is deemed winning and awarded objects to the corresponding bidders. (2) Bidder i who wins kth unit will pay the highest bid of which the failing relay nodes provide, not its own bid.

Then source node S acts as an auctioneer and all the relay nodes take the role of bidders. At the beginning, the auctioneer gives an energy efficiency aim η which stipulates the lowest energy efficiency when one relay node is selected. During the cooperation transmission process, if relay node r_i is chosen to relay the received signal from the source node to the destination node, the received signal at the relay node r_i is a function of P_s, it is denoted as $P_{r_i}(P_s)$. Then, α_i is defined in Eq. (6) as the bid that each relay node sends to the source node

$$\alpha_i(P_s) = k_i P_{r_i}(P_s) \tag{6}$$

where k_i denotes the power price parameter of relay node r_i, according to which we can get the award of r_i, and the reward function is expressed as Eq. (7),

$$R_{r_i} = (k_i - 1)P_{r_i} \tag{7}$$

From Eq. (7) it is known that when $k_i = 1$, r_i gains no profit from helping S but can only cover the cost caused due to the consumed power for the cooperation. When $k_i > 1$, r_i makes a profit of $(k_i - 1)P_{r_i}$. Moreover, r_i has a minimum value of k_i denoted as $k_i^{\min}$ which is also known to r_i $(1 < k_i^{\min} < k_i)$ only. The determination of $k_i^{\min}$ is given as

$$k_i^{\min} = 1 + a\exp(-bq_i^{res}) \tag{8}$$

where $a > 0$, $b > 0$, q_i^{res} denotes the residual battery charge amount of r_i.

As the cooperation relationship of the source node and the relay nodes are supposed as a Vickrey auction model, then for relay node r_i, if it wins the cooperation, the power it needs to spend is the one contained in the minimum bid other relay nodes provide, supposed as $P_{r_i}^*$, then its reward can be denoted as $(k_i - 1)P_{r_i}^*$, else the reward is 0. By increasing k_i, we can get the maximum reward of r_i.

The reward for S is $\Omega_s = P_0 - C_i$, where P_0 is the maximum transmit power of S, C_i is the cost of S cooperating with r_i, given by

$$C_i = P_s + \alpha_i \tag{9}$$

where P_s is the transmission power of source node S.

3 Analysis of the Vickrey auction game

3.1 Bid calculation

Given an energy efficiency aim η at the source node S, the energy efficiency function of Eq. (5) is too complex to obtain the relationship between P_{r_i} and P_s directly. Based on Ref. [9], we know that a higher SNR can make a higher achievable rate, motivated by it, SNR is used instead of transmission rate, thus Eq. (5) is rewritten as

$$\eta = W\Gamma_{s,r_i,d} - u_{r_i}P_{r_i} = \frac{WP_sP_{r_i}g_{r_i,d}g_{s,r_i}}{\sigma^2(P_{r_i}g_{r_i,d} + P_sg_{s,r_i} + \sigma^2)} - u_{r_i}P_{r_i} \tag{10}$$

where u_{r_i} is the price parameter for relay node r_i which can be carefully designed in Ref. [7]. For relay node r_i, the relationship between P_{r_i} and P_s can be given by

$$P_{r_i} = \frac{-(\mu_{r_i}P_sg_{s,r_i} + \mu_{r_i}\sigma^2 + \eta g_{r_i,d} - WP_sg_{s,r_i}g_{r_i,d})}{2\mu_{r_i}g_{r_i,d}} + \frac{\sqrt{[P_s(\mu_{r_i}g_{s,r_i} - Wg_{s,r_i}g_{r_i,d}) + \mu_{r_i}\sigma^2 - \eta g_{r_i,d}]^2 - 4\mu_{r_i}g_{r_i,d}\eta(P_sg_{s,r_i} + \sigma^2)}}{2\mu_{r_i}g_{r_i,d}} \tag{11}$$

According to Eqs (6) and (11), bid α_i of the relay node r_i is got, and the source node S will select relay node r_i with the smallest α_i for help. If r_i is selected, it can keep α_i unchanged which impels it to compete in the next phase of the game successfully. If r_i isn't selected, it can decrease k_i to reduce α_i to win the next game. The initial α_i is obtained by choosing k_i between $k_i^{\min}$ and $k_i^{\min} + 1$, and through RL, it can be maximized gradually.

In order to ensure the Quality of Service (QoS) of the source node, we have to guarantee the minimum rate when the source node cooperates with relay node r_i, and the received rate at the destination node from the source node must achieve a target value ξ. According to Eq. (4), we can get

$$R_{s,r_i,d} = W\log_2\left(1 + \frac{\Gamma_{s,d} + \Gamma_{s,r_i,d}}{\Gamma}\right) \geqslant \xi \tag{12}$$

Based on Eq. (13), we can get

$$P_{r_i} \geqslant \frac{A\sigma^2(P_sg_{s,r_i} + \sigma^2)}{P_sg_{s,r_i}g_{r_i,d} - A\sigma^2g_{r_i,d}} \tag{13}$$

where $((2^{\frac{\xi}{W}} - 1)\Gamma - \Gamma_{s,d}) = A$.

Suppose

$$B = \frac{-(\mu_{r_i}P_sg_{s,r_i} + \mu_{r_i}\sigma^2 + \eta g_{r_i,d} - WP_sg_{s,r_i}g_{r_i,d})}{2\mu_{r_i}g_{r_i,d}} + \frac{\sqrt{[P_s(\mu_{r_i}g_{s,r_i} - Wg_{s,r_i}g_{r_i,d}) + \mu_{r_i}\sigma^2 - \eta g_{r_i,d}]^2 - 4\mu_{r_i}g_{r_i,d}\eta(P_sg_{s,r_i} + \sigma^2)}}{2\mu_{r_i}g_{r_i,d}} \tag{14}$$

According to Eqs (13) and (14), we can get

(1) For any relay node r_i, if $\frac{A\sigma^2(P_sg_{s,r_i} + \sigma^2)}{P_sg_{s,r_i}g_{r_i,d} - A\sigma^2g_{r_i,d}} > B$, then the source node will not choose any relay node for transmission, and it will choose the direct link.

(2) For any relay node r_i, if $\frac{A\sigma^2(P_sg_{s,r_i} + \sigma^2)}{P_sg_{s,r_i}g_{r_i,d} - A\sigma^2g_{r_i,d}} < B$, then the source node will choose the relay node not only with the smallest value in Eq. (11) but also lager than B in Eq. (14).

(3) For any relay node r_i, if $\frac{A\sigma^2(P_sg_{s,r_i} + \sigma^2)}{P_sg_{s,r_i}g_{r_i,d} - A\sigma^2g_{r_i,d}} = B$, then the source node will choose the relay node with the smallest value in Eq. (11) for cooperation.

3.2 Convergence and the Nash equilibrium solution

To prove the convergence of the game, it only needs to prove that the cost function of C_i has a global minimum which can assure an equilibrium point.

For Eq. (9), the following is got

$$C_i = P_s + k_i P_{r_i}(P_s)$$
$$= P_s + \frac{-k_i(\mu_{r_i} P_s g_{s,r_i} + \mu_{r_i}\sigma^2 + \eta g_{r_i,d} - W P_s g_{s,r_i} g_{r_i,d})}{2\mu_{r_i} g_{r_i,d}} +$$
$$\frac{k_i \sqrt{[P_s(\mu_{r_i} g_{s,r_i} - W g_{s,r_i} g_{r_i,d}) + \mu_{r_i}\sigma^2 - \eta g_{r_i,d}]^2 - 4\mu_{r_i} g_{r_i,d}\eta(P_s g_{s,r_i} + \sigma^2)}}{2\mu_{r_i} g_{r_i,d}} \quad (15)$$

By getting the second derivative of C_i in Eq. (15), it is known $\frac{\partial^2 C_i}{\partial P_s^2} \geqslant 0$, then C_i is a convex function with P_s and has a global minimum value. Since C_i is a continuous function, then there exists a Nash equilibrium.

The whole energy efficient transmission scheme based on Vickrey auction game is shown in Table 1.

Table 1 Algorithm based on the Vickrey auction game

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* **Common Knowledge**: $g_{s,d}$, g_{s,r_i}, $g_{r_i,d}$ and W

* **Relay Node** r_i:

(1) Wait for an auction and set

$$P_{r_i} = \frac{-(\mu_{r_i} P_s g_{s,r_i} + \mu_{r_i}\sigma^2 + \eta g_{r_i,d} - W P_s g_{s,r_i} g_{r_i,d})}{2\mu_{r_i} g_{r_i,d}} +$$
$$\frac{\sqrt{[P_s(\mu_{r_i} g_{s,r_i} - W g_{s,r_i} g_{r_i,d}) + \mu_{r_i}\sigma^2 - \eta g_{r_i,d}]^2 - 4\mu_{r_i} g_{r_i,d}\eta(P_s g_{s,r_i} + \sigma^2)}}{2\mu_{r_i} g_{r_i,d}}$$

(2) If $\frac{A\sigma^2(P_s g_{s,r_i} + \sigma^2)}{P_s g_{s,r_i} g_{r_i,d} - A\sigma^2 g_{r_i,d}} > P_{r_i}$, end. Go to Eq. (1).

(3) Choose all the relay nodes satisfying $P_{r_i} \geqslant \frac{A\sigma^2(P_s g_{s,r_i} + \sigma^2)}{P_s g_{s,r_i} g_{r_i,d} - A\sigma^2 g_{r_i,d}}$

(4) Calculate $k_i^{\min}$ using formula Eq. (8), select an initial value of k_i which satisfies $k_i^{\min} < k_i < k_i^{\min} + 1$.

(5) Calculate bid α_i using formula Eq. (6).

(6) Submit bid α_i got by the above to source node S, and wait. Go to (1)

* **Source Node** S:

(1) Set an energy efficiency aim η and a minimum rate aim ξ, announce an auction with an initial P_s.

(2) Compare all the received bids and send a cooperation message to the bidder who provides the minimum α_i.

Go to (1)

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4 Simulation analysis

In this section, the other two energy efficient transmission schemes are given to be compared with the proposed scheme in this paper.

Scheme Ⅰ: the relationship of the source node and the relay node is formulated as a one price auction game, relay node r_i sends its bid α_i got by Eq. (6) to the source node and the one with the smallest bid is chosen and the actual power the relay node spends is the one bid α_i contains.

Scheme Ⅱ, the centralized scheme: in paper Ref. [10], authors proposed a centralized scheme, according to the optimal power allocation P'_{r_i} to relay node r_i, the sum rate of the source node is expressed as

$$R'_{s,r_i,d} = W\log_2\left(1 + \frac{\Gamma_{s,d} + \sum_{i=1}^{N} \frac{P_s P'_{r_i} g_{r_i,d} g_{s,r_i}}{\sigma^2(P'_{r_i} g_{r_i,d} + P_s g_{s,r_i} + \sigma^2)}}{\Gamma}\right) \quad (16)$$

where P'_{r_i} denotes the power relay node r_i spends to help the source node and can be got by Eq. (47) in Ref. [10]. Based on Eq. (5), we can get the energy efficiency of the centralized scheme as follows

$$\eta = R'_{s,r_i,d} - \sum_{i=1}^{N} u_{r_i} P'_{r_i} \quad (17)$$

Assuming that all the channels are independent identical distributed Rayleigh flat-fading, g_{s,r_i} and $g_{r_i,d}$ are random variables obeying the distributions $CN(0,1)$. The main simulation parameters are illustrated in Table 2.

Table 2 Simulation parameters

Parameter	Value
Total system bandwidth B	1MHz
Maximum source transmit power P_0	15W
Gaussian noise power σ^2	1W
Rayleigh fading factor	3
Γ	5dB
λ	1
Maximum relay transmit power $P_{r_i}^{\max}$	10W
P_a	1W

From Fig. 3, we know that in both schemes the total power consumption is increasing as the number of relay nodes grows, that's because when there are more relay nodes, each relay node will do the game with source node S, which causes more power consumption. It is also shown that the whole relay nodes' power consumption is decreasing with the increase of energy efficiency aim η, it is because when η is smaller, the number of relay nodes which can participate in the game is larger, the total power consumption is increasing. From Fig. 3, we also know that the total power consumption of the proposed scheme is larger than scheme I when the number of relay nodes and the value of η are the same, that's because when the energy efficiency aim η is the same, the power that the relay nodes in the proposed scheme winning the cooperation needs to spend is the one contained in the minimum bid provided by other relay nodes, and it's larger than the power the relay's own bid contains in the one price auction game scheme.

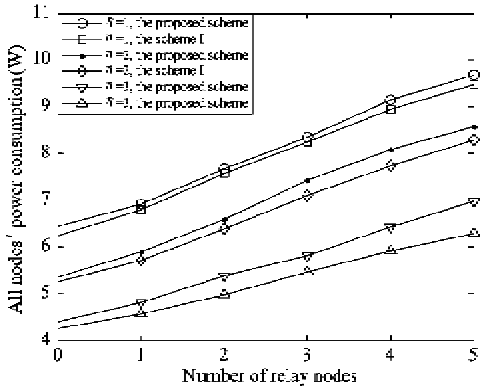

Fig. 3 Total power consumption with different number of relay nodes

From Fig. 4, it is known that the source node's rate is increasing with the growth of the number of relay nodes and the energy efficiency aim η under the three schemes. And in the proposed scheme and scheme I, when source node S chooses the relay node for cooperation, it first considers the energy efficiency and discards the relay nodes which are not energy efficient, which causes the rate lower than the centralized scheme. As η grows larger, more relay nodes are discarded and the source node's rate is becoming smaller. From Fig. 4, it's also known that when the number of relay nodes and the energy efficiency aim η are the same, the source node's rate of the proposed scheme is larger than scheme I, since when the energy efficiency aim η is the same, the power in the proposed scheme spent by the relay node is larger than that of scheme I. According to Eq. (4), the source node's rate in the proposed scheme is larger than that of scheme I.

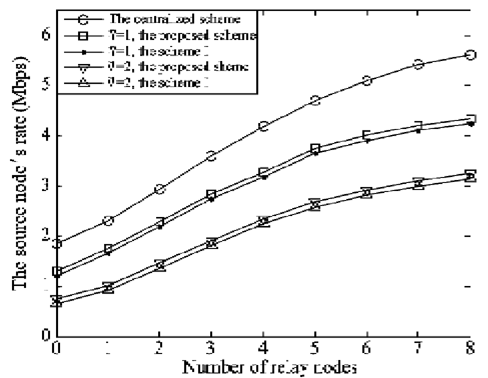

Fig. 4 The source node's rate under the two schemes

5 Conclusions

This paper focuses on the problem of energy efficient transmission in one source multi-relay cooperative communication network, aims to find the most energy-efficient relay node for the source node when the source node broadcasts a cooperative request. To impel the relay nodes to send the minimum bid as much as possible, the interaction of the source node and the relay nodes is modeled as a Vickrey auction game, when the source node needs help, the relay node having minimum bid calculated by the energy efficient function is selected, but the actual power it has to spend is the power involved in the smallest bid provided by the failing relay nodes.

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