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Energy-efficient relay selection for multicast communication

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Abstract

Aimed at the problem that system energy consumption of the traditional cooperative multicast is large with increase of the number of users, four energy-efficient relay selection schemes are proposed to reduce system energy consumption. By using exhaustive search method, the optimal relay selection algorithm selects relays from all the possible combinations of relays, the scheme could reduce energy consumption and improve energy efficiency effectively at high computational complexity. According to the thought of iteration, greedy algorithm chooses relays using the selected relays, though the scheme doesn't achieve the energy efficiency of the optimal relay selection algorithm, it reduces computational complexity. Besides, relay selection based on multicast rate of users selects relays using the multicast rate of each user by which the rest users with bad channel condition could decode data correctly, and relay selection based on channel state information (CSI) among users chooses relays according to the whole CSI between each user decoded data correctly and all users failed to decode data, these two schemes further reduce complexity compared to greedy algorithm. Results show that all the proposed energy-efficient relay selection approaches could improve energy efficiency while meeting the requirement of fairness.

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Keywords: Cooperative multicast, energy, relay selection;

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1. Introduction

A great many cooperative multicast methods which have a trade-off between high throughput and good fairness have been researched many years. Cooperation based on network coding [1-2] improves the system throughput effectively, but the limited improvement of performance is at the cost of increase the time delay. Other approach used space-time code [3-4] reduces outage probability and guarantees the fairness among users, but it is hard to be realized because of strict request of code synchronization. Two-stage cooperative multicast based on decode-and-forward (DF) protocol is investigated in [5], i.e. traditional two-stage cooperation. at the first stage BS multicasts data at a high transmission rate, only users with good channel conditions can decode data correctly, then at the second stage all the relays multicast data to the rest of users. The scheme improves system throughput, but system energy consumption is considerable when the number of users is large. Therefore the problem of energy consumption is investigated in [6-9]. Threshold-based relay selection protocol is proposed in [6], with amplify-and-forward (AF) mode the selected relays forward data to users failed to decode data, the method reduces system energy consumption, but it only applies to the network with relays distributed at fixed positions. By using location information among users, nearest-neighbor algorithm is proposed in [7]. Though this scheme could reduce the number of relays to some degree, it couldn't reduce energy consumption effectively because of not fully considering the channel conditions among users. And another energy-efficient cooperation scheme [8] is proposed, where the user failed to decode data at the first stage sends a message asking for help, then users decoded data correctly in the transmission boundary take part in cooperation. The scheme could reduce energy consumption to a certain degree, but it is only a theory analysis of the probability that users decoded data correctly are chosen as relays, and not sure which user should be chosen as relay. Therefore, in order to reduce system energy consumption and improve energy efficiency while meeting the requirement of fairness, four energy-efficient relay selection methods are investigated as follows.

2. System model

Considering a wireless multicast network in [5] with a circular cell of radius R, the BS is located at the center of the cell and multicasts to N users who are uniformly and randomly located within the cell. Using the idea of two-stage cooperative multicast, Firstly, BS multicasts data to all users at a rate r_1 in the time interval T_1, and then the chosen relays multicast data to those users failed to receive data with a rate r_2 in the time interval T_2. To ensure all the users receiving the same data, the data transmitted in the two stages should satisfy $r_1T_1=r_2T_2=S_T$, where S_T is the length of data packet. All users in the network work are in the half-duplex mode, that is, they can't transmit and receive in the same frequency band at the same time. At the first stage, BS broadcasts data to all the users, for the user i ($1\le i\le N$) located at (l_i, θ_i), $0<l_i<R$, $0 \le \theta_i \le 2\pi$, the receiving signal-to-noise ratio(SNR) is $\gamma_i^{sd} = P_{BS} \,|\, h_i \,|^2\, l_i^{-\alpha} / N_0$, where the superscript 'sd ' means that BS multicasts data to users; P_{BS} is the transmission power of BS; $l_i^{-\alpha}$ is the path loss of user i; α is path loss coefficient; h_i, which is a zero-mean circularly symmetric complex Gaussian random variable with unit variance, namely $h_i \sim CN(0,1)$, is the small scale channel fading experienced by the user i; and N_0.is the variance of the additive white Gaussian random variable. Therefore the maximum attainable rate of user i is given by $r_i^{sd} = W \log_2(1+\gamma^{sd}{}_i)$, where W is the system band. Define coverage rate C, which is the proportion of users could decode data correctly at the first stage, and the coverage rate determines the data transmission rate at the first stage. Compute the instantaneous receiving SNR of all users at the first stage, and arrange all the SNR in descending order, get the SNR vector $\boldsymbol{SNR}=[\gamma^{sd}{}_1,\gamma^{sd}{}_2,\ldots\gamma^{sd}{}_{NC},\ldots\gamma^{sd}{}_N]$, so the set of users decoded data correctly is $G=\{1,2,3,\ldots,NC\}$, the set of users failed to decode data is $B=\{NC+1,NC+2,\ldots,N\}$, and the multicast rate at the first stage can be expressed as

$$r_1 = W\log_2(1+\gamma_{NC}^{sd}) \tag{1}$$

The transmission time at the first stage is given by $T_1=S_T/r_1$, and the energy consumption at the first stage is

$$E_1 = (P_{BS} + NP_R)T_1 \tag{2}$$

where P_R is the receiving power of each user. At the second stage, N_x users in G are selected as relays, the corresponding relay set is R_e, and then these relays forward data to the users in B. In order to make all users decode data correctly in the two stages, relays multicast data at a rate that user with worst CSI could decode correctly. Therefore multicasting rate of relays at the second stage is

$$r_2 = W\log_2(1+\min(\gamma_j^{rd})) = W\log_2(1+\min(P_{RE}\,|\sum_{i=1}^{N_x}\sqrt{l_{i,j}^{-\alpha}}h_{i,j}|^2/N_0)) \quad \forall \quad j\in B \tag{3}$$

where the superscript ‘ rd ’ means that relays multicast data to the users; $l_{i,j}$ is the distance between relay i and user j; $h_{i,j}$, which is small scale channel fading, has the same probability distribution as h_i ; and P_{RE} is the transmission power of each relay. Then multicast time at the second stage is $T_2=S_T/r_2$, the energy consumption at the second stage is

$$E_2 = (N_x P_{RE} + N(1-C)P_{\mathrm{R}})T_2 \tag{4}$$

The system energy efficiency of the whole process in the two stages can be expressed as

$$\eta = \frac{NS_T}{E_1+E_2} = \frac{NS_T}{(P_{BS}+NP_R)T_1 + (N_x P_{RE} + N(1-C)P_R)T_2} \tag{5}$$

Due to the P_{BS}, P_{RE} and P_R is fixed, it’s easy to see that system energy efficiency is subject to the time in the two stages, the number of relays and coverage rate C from (5). Because the time at the first stage and the number of relays dependents on the coverage rate C, the time in the second stage is conditioned to the minimum receiving SNR of the users in this stage, and the minimum receiving SNR is decided by the relays, therefore the problem of maximizing system energy efficiency can be transformed into the problem of selecting optimal relay set in the best coverage rate. Substitute (1) and (3) into (5), $\forall j\in B$ the problem of maximum energy efficiency is formulated as follows:

$$(C^*, R_e^*) = \arg\max \frac{N}{\dfrac{(P_{BS}+NP_R)}{W\log_2(1+\gamma^{sd}{}_{NC})} + \dfrac{(N_x P_{RE} + N(1-C)P_R)}{W\log_2(1+\min(\gamma_j^{rd}))}} \tag{6}$$

where C^* and R^*_e are the best coverage rate and optimal relay set respectively, when the system achieves the maximum energy efficiency. Because it’s hard to solve the problem directly, using statistical method we first count the relay set under the maximum energy efficiency in a given coverage rate, then compare the maximum energy efficiency in different coverage rate, and choose corresponding relay set under the maximum energy efficiency as the final relay set.

3. Energy efficiency relay selection algorithms

3.1. The optimal relay selection algorithm

By using exhaustively search method, we get the optimal relay selection algorithm. The algorithm works as follows:

Step1: Arrange all the instantaneous receiving SNR of all users at the first stage in descending order, get the SNR vector ***SNR***. For a given coverage rate *C*, get the set *G* where users could decode data correctly and the set B where users are failed to decode data, and calculate energy consumption at the first stage.

Step2: For *i*=1 to *NC*, Select *i* user/users from *G* randomly as a relay/relays, estimate all possible multicast rate in the second stage, select maximum from C_{NC}^{i} rate as multicast rate r_{2i} under the condition of the *i* relay/relays, and get the corresponding relay set Re_i.

Step3: For *i*=1 to *NC*, Substitute rate r_{2i} and corresponding relay set Re_i into (4), count energy consumption E_{2i} in the second stage. The relay set for the given coverage rate *C* can be expressed as $R_e = \arg\min_{Re}\{E_{2i}\}\ (1 \le i \le NC)$ and the system energy efficiency for the given coverage rate *C* is $\eta = NS_T / (E_1 + \min\{E_{2i}\})\ \ (1 \le i \le NC)$.

Step4: Compare system energy efficiency under different coverage rate, the final chosen relay set is the set under the maximum system energy efficiency.

By comparing the energy efficiency for all possible combinations of the relays, the optimal relay selection algorithm selects relays of the maximum energy efficiency. Obviously, the algorithm could find the optimal relay set and achieve the maximum energy efficiency, but the computational complexity is very high, and the computational complexity is $O(2^{NC}N(1\text{-}C)+NC)=O(2^{NC}N)$.

3.2. Greedy algorithm

In order to reduce the computational complexity of the optimal relay selection algorithm, the greedy algorithm is proposed using the method of iteration. The specific steps are as follows:

Step1: The same as the step1 of the optimal relay selection algorithm.

Step2: Choose one element randomly from the set *G* as a relay, estimate all possible multicast rate in the second stage, select the maximum from C_{NC}^{1} rate as multicast rate r_{21} under the condition of one relay, and the corresponding relay forms relay set Re_1.

Step3: Choose two users form the set *G* as relays, one is chosen in the step2, the other is chosen randomly from the rest *NC-1* users in the set *G*, estimate all possible multicast rate in the second stage, select the maximum from *NC-1* rate as multicast rate r_{22} under the condition of the two relays, and the corresponding two relays form the relay set Re_2.

Step4: For *i*=3 to *NC*, choose *i* users from the set *G* as relays, where *i-1* elements are the relays that are chosen when there exactly are i-1 users taking part in cooperation, the other one is chosen randomly from the rest *NC-i+1* users in the set *G*, estimate all possible multicast rate in the second stage, select maximum from *NC-i+1* rate as multicast rate r_{2i} under the condition of *i* relays, and the corresponding *i* relays form the set Re_i.

Step5: The same as the step3 of the optimal relay selection algorithm.

Step6: The same as the step4 of the optimal relay selection algorithm.

By using iteration, the relay selection of greedy algorithm depends on the last choice of relays, and the number of relays selected in this time is one more than last time. Though greedy algorithm may not be able to find the optimal relay set, it could reduce computational complexity largely, and computational complexity can be expressed as $O((NC(NC+1)N(1\text{-}C)/2+NC))=O(N^3)$.

3.3. Relay selection algorithm based on multicast rate of users

Greedy algorithm could reduce computational complexity compared to the optimal relay selection algorithm, but its computational complexity is still quite high when the number of users in the network is large, therefore relay selection algorithm based on multicast rate of users is proposed. We estimate the multicast rate which ensures all users in B decode data correctly under the condition of only one user is chosen as a relay, arrange all multicast rate in descending order, and then choose the relay. The algorithm works as follows:

Step1: The same as the step1 of the optimal relay selection algorithm.

Step2: For each user $i \in G$, estimate the multicast rate r_i which ensures all users in B decode data correctly on condition that only one user in G is chosen as a relay.

Step3: Arrange the NC multicast rate in step2 in descending order, get the rate vector ***Rate***. For $k=1$ to NC, select the first k element/elements of the ***Rate*** as a relay/relays, the corresponding relay set is Re_k, estimate the multicast rate r_{2k} in the second stage on condition that k relay/relays take parting in cooperation.

Step4: Substitute rate r_{2k} and corresponding relay set Re_k into (4), count energy consumption E_{2k} in the second stage, the relay set for the given coverage rate C can be expressed as $R_e = \arg\min_{Re_k}\{E_{2k}\} \quad (1 \le k \le NC)$, and compute the energy efficiency for the given coverage rate .

Step5: The same as the step4 of the optimal relay selection algorithm.

The computational complexity of this scheme is $O(NC(N(1\text{-}C))+NC(N(1\text{-}C))+NC)=O(N^2)$.

3.4. Relay selection algorithm based on CSI among users

Relay selection algorithm based on multicast rate of users chooses relays according to the multicast rate that ensures all users in B decode data correctly in the case of only one relay, and it only considers channel condition between each user in G and the user with the worst channel condition in B without considering the whole CSI among each user in G and all users in B, when a plurality of relays take part in cooperation and forward data, the multicast rate in the second stage is related to each relay and all users in B, so relay selection algorithm based on CSI among users is investigated, the specific steps are as follows:

Step1: The same as the step1 of the optimal relay selection algorithm.

Step2: For each user $i \in G$, estimate the overall channel fading variable H_i between user i in G and all users in B, H_i reflects the overall channel state between user i in G and all users in B, and H_i can be expressed as $H_i = \left| \sum_{j=1}^{N(1-C)} \sqrt{l_{i,j}^{-\alpha}}\, h_{i,j} \right| / \sum_{j=1}^{N(1-C)} \left| \sqrt{l_{i,j}^{-\alpha}}\, h_{i,j} \right| \quad j \in B$.

Step3: Arrange all channel fading variable H_i in descending order, get the channel fading vector $\boldsymbol{H}$. For $k=1$ to NC, select the first k element/elements of the $\boldsymbol{H}$ as a relay/relays, and the corresponding relay set is Re_k , estimate the multicast rate r_{2k} in the second stage on condition that k relay/relays take parting in cooperation.

Step4: The same as the step4 of relay selection algorithm based on multicast rate of users.

Step5: The same as the step5 of relay selection algorithm based on multicast rate of users.

The computational complexity of this scheme is $O(NC(N(1\text{-}C))+NC(N(1\text{-}C))+NC)=O(N^2)$.

4. Simulation results

In this section, we set R=100m, α=3, B=10 kHz, S_T=1000 bits, P_{BS}=1w, P_{RE}=0.1w and P_R=0.05w, and define the energy efficiency as the number of bits transmitted when one joule energy is consumed. For clarity of presentation, we simplify traditional cooperation, optimal relay selection algorithm, and greedy algorithm, relay selection algorithm based on multicast rate of users and relay selection algorithm based on CSI among users as TC, OPT, Greedy, RS-Rate, RS-CSI, respectively.

In Fig.1, we compare the system energy efficiency of different cooperative multicast schemes verse different coverage rate C on condition that transmission SNR of BS is 40 db. It can be seen that energy efficiency of proposed four schemes is much greater than TC, and the coverage rate is different when all kinds of relay selection methods achieve maximum energy efficiency, because these relay selection methods choose relay according to different principles. And we should note that OPT can select the most suitable relay set and achieve the optimal performance at the cost of high complexity using exhaustive search method; besides, Greedy chooses relays according to the relays that have been selected using iteration, its energy efficiency is inferior to OPT but superior to RS-Rate and RS-CSI; what' more, energy efficiency of RS-CSI is slightly higher than the energy efficiency of RS-Rate, though their energy efficiency is less than OPT and Greedy, these two methods reduce the computational complexity effectively, especially when the number of users is large.

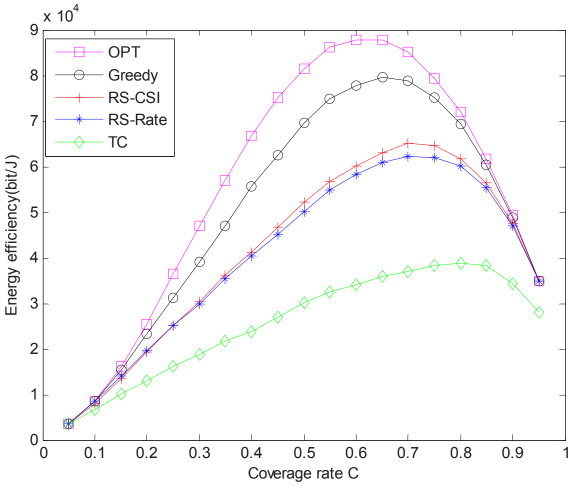

Fig. 1. Energy efficiency vs. coverage rate C

In Fig 2, we compare maximum system energy efficiency of different methods when transmission SNR of BS varies from 30 dB to 60 dB. The results show that maximum system energy efficiency of all the schemes improves with the increasing of transmission SNR of BS, and the maximum system energy efficiency of the proposed four relay selection methods is superior to the method of TC, especially when the SNR is large; besides, the maximum system energy efficiency of OPT is higher than greedy algorithm, and the maximum system energy efficiency of greedy algorithm is higher than RS-Rate and RS-CSI; what's more, the maximum energy efficiency of RS-Rate and RS-CSI is approximately equal, the performance of RS-CSI is much closer to the OPT than RS-Rate.

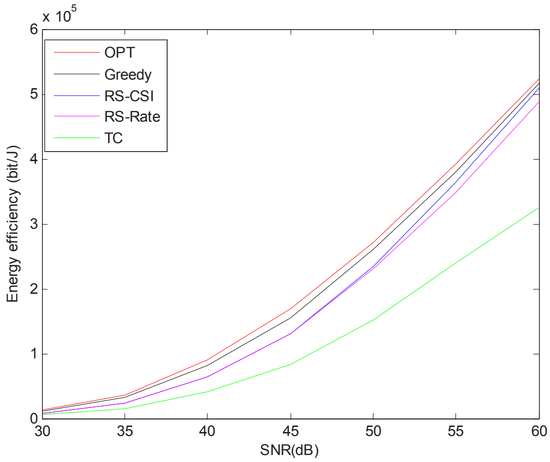

Fig. 2. The maximum energy efficiency vs. transmission SNR of BS

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