Joint Selection of On/off Relay Mode and Adaptive Modulation Mode for Green Cooperative Multicast Networks

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***Abstract*—Increasing concerns about climate change are generating significant interest among researchers in reducing the energy consumption of existing communication infrastructure. However, previous research into the efficiency of cooperative communication networks only considers throughput or energy consumption separately. In response, this paper explores the trade-off between these two important factors and proposes maximizing energy efficiency, defined as the ratio of throughput over energy consumption. Because recent research demonstrates that machine operations require more energy, we propose optimally switching off unnecessary relays, while efficiently exploiting adaptive modulation (AM) to ensure that all multicast users can be served simultaneously under a required bit error rate. However, finding the optimal on/off relay mode and AM mode is challenging due to numerous possibilities required to be carefully considered and examined. To address this issue, we design an energy efficiency-aware search algorithm (EESA) to find the optimal solution. Our simulation results demonstrate that EESA is able to effectively improve the energy efficiency in cooperative multicast networks.**

I. Introduction

Recently, studies have shown that the rapid development of Information and Communication Technology (ICT) is contributing to global warming and climate change due to the increase in energy consumption and CO2 emissions [1]. As a result, green communications and green networks are generating a great deal of interest in both academia and industry. Energy efficient hardware (e.g. low power base stations [2]) and renewable energy source (e.g. solar energy [3]) are being incorporated into the design of next generation infrastructures. Nevertheless, it is also important to develop energy efficient strategies for existing infrastructure.

In cooperative communication networks, most early works on unicast and multicast did not regard the reduction of energy consumption as their main objective. For unicast, the proposed strategies, such as the position [4], selection [5], and power allocation [6] of relays, focused on improving the received signal strength, reducing the outage probability and bit error rate (BER), or increasing the throughput. Meanwhile, algorithms for multicast routing [7], scheduling [8], and relay assignment [9] were designed to guarantee service availability for all multicast destinations. Recently however, minimization of network energy consumption has been regarded as an important objective. Proposed approaches for cooperative unicast have included the adjustment of transmission power [10] and the deployment of relays [11]. Different strategies for cooperative multicast routing [12] and destination selection [13] have also been proposed to reduce the total energy consumption in transmission.

One downside to reducing transmission energy is a subsequent decrease in throughput. In response, this paper explores the trade-off between energy consumption and throughput for green networks. Rather than maximizing throughput or minimizing energy consumption separately, we maximize energy efficiency, which is defined as the ratio of throughput over energy consumption, for decode-and-forward (DF) cooperative multicast networks. Previous work on adjusting the power levels did not notice that most energy consumption at a base station or relay station is not induced from the transmission energy. In contrast, recent research demonstrates that the machine operations require more energy [14] [15]. In other words, during off peak times, aggregating the traffic into fewer stations leads to smaller energy consumption, as compared to distributing the traffic to more stations with a small transmission power. Therefore, this paper maximizes efficiency by exploiting a binary on/off relay mode and adaptive modulation (AM) so that only necessary relays are active. The trade-off between throughput and energy consumption is carefully examined by jointly selecting the on/off relay mode and AM mode to maximize energy efficiency in cooperative multicast networks.

Maximizing energy efficiency in this manner is challenging, due to the numerous possibilities for on/off relays and modulation that must be considered. To efficiently identify the optimal relay mode and AM mode, we propose an energy efficiency-aware search algorithm (EESA), which prioritizes the candidate relay mode and AM mode that are more energy efficient. Therefore, EESA significantly reduces the time required to find the optimal solution. The simulation results demonstrate that energy efficiency can be effectively improved by switching unnecessary relays off. In addition, compared with previous work, the results indicate that our objective function, energy efficiency, is able to effectively strike a balance between energy consumption and throughput in cooperative multicast networks.

The remainder of this paper is organized as follows. In Section II, we describe the system models. Section III formulates the problem and presents the proposed algorithm. Section IV demonstrates our simulation results, while Section V contains some concluding remarks.

II. System Models

This section describes the system models considered in this paper, namely, DF cooperative multicast network (Section II-A), the channel model (Section II-B), and AM (Section II-C).

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A. Decode-and-forward Cooperative Multicast Network

The cooperative multicast network considered in this paper is comprised of a source (S), N_r relays (R_i, $i = 1 \ldots N_r$), and N_d multicast destinations (D_j, $j = 1 \ldots N_d$). Each relay is equipped with a single antenna for half-duplex transmissions. We consider the on/off mode, DF protocol, and time division multiple access (TDMA) for the relays. A possibility of on/off relay modes is represented by a $1 \times N_r$ vector, $\overline{\lambda} = [\lambda_1 \ldots \lambda_{N_r}]$, where $\lambda_i = 1$ and 0 denotes that R_i is switched on and off alternatively. In each TDMA cooperative transmission, T is the length of each time slot for S and the relays. Specifically, S broadcasts a modulated symbol to the relays and destinations in the first slot. In the tth slot, for $t = 2, \ldots, \sum_{i=1}^{N_r} \lambda_i + 1$, the active relays alternately forward the symbol to the destinations with the same modulation, where $\sum_{i=1}^{N_r} \lambda_i$ equals the number of active relays. Finally, the destinations using maximal ratio combining (MRC) combine the duplicate signals from S and the relays to take advantage of cooperative diversity. In addition, the N_r relays lead to 2^{N_r} possibilities of on/off relay modes, and these possibilities are included by a set Λ, i.e. $\overline{\lambda} \in \Lambda$.

Given a possibility of relay modes $\overline{\lambda}$ in the above cooperative multicast network, the total energy consumption of an entire cooperative transmission is described below:

$$EC\left(\overline{\lambda}\right) = \left(P_S^{tr} + P_S^{hw} + \sum_{i=1}^{N_r} \lambda_i (P_R^{tr} + P_R^{hw})\right) T,$$

which increases with the number of active relays, where P_S^{tr} and P_S^{hw} are respectively the transmission power and hardware power of S. P_R^{tr} and P_R^{hw} are the transmission power and hardware power of each active relay. In addition, for cellular networks, P_S^{hw} (for the base station) is larger than P_R^{hw} (for the relay station) due to additional hardware requirements, e.g. the wired backhaul connection. Therefore, we let $P_S^{hw} = \beta_1 P_R^{hw}$ with $\beta_1 \geq 1$. Because machine operations consume more power than transmission actions, we let $P_S^{hw} = \beta_2 P_S^{tr}$ and $P_R^{hw} = \beta_3 P_R^{tr}$, where $\beta_2 \geq 1$ and $\beta_3 \geq 1$. Here, transmission power control can also be considered as a whole with the selection of the on/off relay mode to improve energy efficiency. Nevertheless, due to space constraints, we regard this as an area for future research.

B. Channel Model

The channel model considers the effects of additive noise, path loss, and Rayleigh fading for all links. For the link from S to R_i, the received signal of R_i is expressed as $y_{si} = (d_{si}/d_0)^{-\alpha} h_{si} \sqrt{P_S^{tr} T} x + \eta_{si}$. The subscript of y_{si} denotes S-R_i. The signal y_{si} includes the following components: the transmission energy used by S to transmit the modulated symbol x is $P_S^{tr} T$; the additive noise η_{si}, which is characterized as a zero-mean complex Gaussian random variable with variance $\mathcal{N}_0$; the path loss effect $(d_{si}/d_0)^{-\alpha}$, which considers the signal attenuation of radio propagation through S-R_i with propagation distance d_{si}, exponent α, and reference distance d_0 [16]; and finally the fading coefficient h_{si}, which is modeled as a zero-mean complex Gaussian random variable with unit variance. The SNR of y_{si} is $\gamma_{si} = (d_{si}/d_0)^{-2\alpha} |h_{si}|^2 P_S^{tr} T / \mathcal{N}_0$. Similarly, the signal from R_i to D_j is given by $y_{ij} = (d_{ij}/d_0)^{-\alpha} h_{ij} \sqrt{P_R^{tr} T} x + \eta_{ij}$, for $i = 0 \ldots N_r$ and $j = 1 \ldots N_d$. The propagation distance, the fading coefficient, and the additive noise are notated by d_{ij}, h_{ij}, and η_{ij} respectively. The SNR of y_{ij} is $\gamma_{ij} = (d_{ij}/d_0)^{-2\alpha} |h_{ij}|^2 P_R^{tr} T / \mathcal{N}_0$. Note that $i = 0$ corresponds to S (i.e. $R_0 \equiv S$) throughout this paper.

C. Adaptive Modulation

The constant-power discrete-rate AM considered in this paper are BPSK ($m = 1$ and $B_1 = 1$), QPSK ($m = 2$ and $B_2 = 2$), and the higher modulations 2^{B_m}-QAM ($m = 3 \ldots M$ and $B_m = 2(m-1)$). In these modulations, m represents the AM mode, M is the highest AM mode, and B_m is the number of bits per symbol of m. Moreover, m can be supported by a relay and a destination if the instantaneous received SNR exceeds the minimal required SNR Γ_m, such that the BER of m is lower than the target BER, say BER$_T$. Specifically, the instantaneous received SNR of a relay is the link SNR of its source-relay link, while the combined SNR of a destination with MRC is regarded as its instantaneous received SNR. To satisfy BER$_T$, the minimal required SNR of m, Γ_m, is obtained by solving $\text{BER}_T - b_m Q\left(a_m \sqrt{\Gamma_m}\right) = 0$ [17] [18], where $b_m Q\left(a_m \sqrt{\Gamma_m}\right)$ is an approximated BER of m given SNR Γ_m [19]. The result is that $\Gamma_m = \left[\frac{1}{a_m} Q^{-1}\left(\frac{\text{BER}_T}{b_m}\right)\right]^2$, where $(a_1, b_1) = (\sqrt{2}, 1)$, $(a_2, b_2) = (1, 1)$, and $(a_m, b_m) = \left(\sqrt{\frac{3}{2^{B_m}-1}}, \frac{4(\sqrt{2^{B_m}}-1)}{B_m \sqrt{2^{B_m}}}\right)$ for $m = 3 \ldots M$. In addition, the throughput is measured by bits per symbol in this paper.

III. Problem Formulation and the Proposed Algorithm

A. Problem Formulation

To effectively balance the trade-off between energy consumption and throughput, we jointly select the on/off relay mode and AM mode to maximize energy efficiency. Specifically, we switch unnecessary relays off to save energy, while the active relays are required to guarantee service availability for all multicast destinations with the selected AM mode. We also ensure that all multicast destinations can receive data that fulfills the BER requirement. Given the link SNRs, γ_{si} and γ_{ij}, $\forall i, j$, the maximization problem is formulated as follows:

$$\left(\overline{\lambda}^*, m^*\right) = \arg \max_{(\overline{\lambda}, m) \in \Lambda \times \{1 \ldots M\}} \left\{ \frac{B_m}{EC\left(\overline{\lambda}\right)} \right\} \quad (1)$$

$$\text{s.t.} \quad \gamma_{si} \geq \lambda_i^* \Gamma_{m^*}, \forall i \quad (2)$$

$$\gamma_{0j} + \sum_{i=1}^{N_r} \lambda_i^* \gamma_{ij} \geq \Gamma_{m^*}, \forall j, \quad (3)$$

where $(\overline{\lambda}^*, m^*)$ with $\overline{\lambda}^* = [\lambda_1^* \ldots \lambda_{2^{N_r}}^*]$ is the optimal solution of on/off relay mode and AM mode that maximizes the energy efficiency in (1). Note that there exist multiple solutions maximizing energy efficiency, and they are regarded as equally good; Section III-B provides an example to explain this point further. Moreover, constraint (2) ensures that the active relays with $\lambda_i^* = 1$ can decode the source's transmitted symbols (i.e. $\gamma_{si} \geq \Gamma_{m^*}$), while constraint (2) is relaxed if $\lambda_i^* = 0$ (i.e. $\gamma_{si} \geq 0$). To satisfy the BER requirement, constraint (3) stipulates that for $j = 1 \dots N_D$, the combined SNR at D_j given $\overline{\lambda}^*$, $\gamma_{0j} + \sum_{i=1}^{N_r} \lambda_i^* \gamma_{ij}$, must exceed the minimal required SNR of m^*. In addition, the possibilities of on/off relays increase exponentially with the number of relays, resulting in high time complexity to solve (1). To address this problem, we propose EESA, described below.

B. Energy Efficiency-aware Search Algorithm (EESA)

Instead of employing an exhaustive search for the optimal solution of on/off relay mode and AM mode, we devise EESA to efficiently find the solution. EESA considers a search order for the candidate solutions, which with higher priority are first examined to discern whether all multicast destinations can be served with the required BER. EESA terminates when the first feasible solution that satisfies constraints (2) and (3) is obtained. To ensure that the first feasible solution is optimal, EESA jointly considers the two priority strategies described as follows.

1) High Energy Efficiency First: To maximize the energy efficiency in (1), the candidate solution with better energy efficiency enjoys a higher priority in the search order. Therefore, EESA first considers the candidate solution leading to the highest energy efficiency with no active relay and the highest supportable AM mode. Note that the AM modes that are unable to support all multicast destinations, even when all relays are active, can never act as a supportable AM mode for any feasible solution. Since in most cases not all destinations can be served, EESA finds the candidate solutions that have the second highest energy efficiency. EESA does not need exhaustive search to find the candidate solutions, because the candidate solutions can be found by decreasing the energy efficiency stepwise, i.e., increasing the number of active relays by one or lowering the AM mode by one level. Similarly, the priority of the remaining candidate solutions is identified according to their energy efficiency. In the above search order, the first candidate solution satisfying constraints (2) and (3) is the optimal solution for (1), because no candidate solution with higher priority is available for the multicast service and no candidate solution with lower priority achieves a higher energy efficiency.

2) High Density of Nearby Destination First: When multiple candidate solutions have the same energy efficiency with the same number of active relays, it is not guaranteed that each of them will be able to serve all multicast destinations, because the active relays are different for each solution. Therefore, EESA prioritizes the candidate solution that is more inclined to support all multicast destinations, and the active relays in this case usually have more nearby destinations. With this observation, EESA calculates the average distance of relay-destination links to evaluate the priority of different candidate solutions. Specifically, given a candidate solution with on/off relay modes $\overline{\lambda}$, the average distance of relay-destination links of active relays is $d_{\overline{\lambda}}^{avg} = \left(\sum_{i=1}^{N_r}\sum_{j=1}^{N_d} \lambda_i d_{ij}\right) / \left(\sum_{i=1}^{N_r} \lambda_i N_d\right)$, which is the sum of relay-destination distance over the number of relay-destination links (i.e. $\sum_{i=1}^{N_r} \lambda_i N_d$). Evaluating the average distance of relay-destination links enables EESA to avoid examining the candidate solutions with unnecessary relays (i.e, the relays serving no multicast destination), thereby effectively reducing the search iterations required in EESA.

Consider the following intuitive example with two relays (i.e. $\Lambda = \{[0\ 0], [0\ 1], [1\ 0], [1\ 1]\}$), three AM modes (i.e. BPSK, QPSK and 16-QAM), and $P_R^{tr} + P_R^{hw} = 0.83(P_S^{tr} + P_S^{hw})$). We assume that 16-QAM is too high to guarantee the required BER under the present channel condition. In addition, we assume that the second relay, which is farther from the source, has more nearby multicast destinations (i.e. $d_{\overline{\lambda}}^{avg}|_{\overline{\lambda}=[1\ 0]} > d_{\overline{\lambda}}^{avg}|_{\overline{\lambda}=[0\ 1]}$). Therefore in this example the multicast service must have an active second relay to ensure multicast service. The energy efficiency of each candidate solution is shown in Table I for reference, where the energy efficiency score is normalized by $1/(P_S^{tr} + P_S^{hw})T$.

TABLE I
NORMALIZED ENERGY EFFICIENCY ($B_m/(\sum_{i=1}^{N_r} 0.83\lambda_i + 1)$)

	$m=1$	$m=2$	$m=3$
$\overline{\lambda} = [0\ 0]$	1/1=1	2/1=2	4/1=4
$\overline{\lambda} \in \{[0\ 1], [1\ 0]\}$	1/1.83=0.55	2/1.83=1.09	4/1.83=2.19
$\overline{\lambda} = [1\ 1]$	1/2.66=0.38	2/2.66=0.75	4/2.66=1.50

Below, we further describe the search order and demonstrate how EESA searches for the optimal solution in this example.

According to the first priority strategy, EESA begins by considering $([0\ 0], 2)$ with the highest energy efficiency, while $(\overline{\lambda}, 3)|_{\forall\overline{\lambda}\in\Lambda}$ with 16-QAM are unavailable for the multicast service. Since QPSK with no active relay cannot satisfy constraint (3), EESA then finds the candidate solutions, $([0\ 1], 2)$ and $([1\ 0], 2)$, that have the second highest energy efficiency, by increasing the number of active relays by one. According to the second priority strategy, EESA evaluates the average distance of relay-destination links of the relays, and thereby examines whether constraints (2) and (3) are satisfied for $([0\ 1], 2)$ that has a smaller average distance of relay-destination links. If $([0\ 1], 2)$ satisfies constraints (2) and (3), EESA selects it as the optimal solution and terminates the search iterations; otherwise, according to the priority strategies mentioned above, the search order of remaining candidate solutions is $([1\ 0], 2)$, $([0\ 0], 1)$, $([1\ 1], 2)$, $([0\ 1], 1)$, $([1\ 0], 1)$, and $([1\ 1], 1)$. Note that if each solution of $([0\ 1], 2)$ and $([1\ 0], 2)$ satisfies (1)–(3), both solutions are the optimal solution in this example.

IV. SIMULATION RESULTS

This section presents our simulation results. We consider a one-dimensional network (e.g. the highway scenario [11]). The source is located at the origin, and the relays are randomly distributed within the range $(0, d_{\max}]$, where $d_{\max} = 1000$ m. Moreover, we consider the cluster of multicast destinations, and thereby randomly distribute the multicast destinations within a specific range $(d_{\text{near}}, d_{\text{far}}]$, where $0 \leq d_{\text{near}} < d_{\text{far}} \leq d_{\max}$. In our simulation, we let $P_S^{tr} = P_R^{tr} = 25.88$ dB to support the lowest rate communications (with BPSK) for $\text{BER}_T = 10^{-3}$ and the propagation distance 900 m. Other parameters are set as follows: $N_d = 100$, $M = 5$, $\alpha = 2$, $d_0 = 100$ m, $\beta_1 = 1.2$, and $\beta_2 = \beta_3 = 1.5$.

Figs. 1 and 2 compare the energy efficiency and energy consumption (both are normalized by $1/P_R^{tr}T$) with and without switching on/off relay mode. When the number of relays is

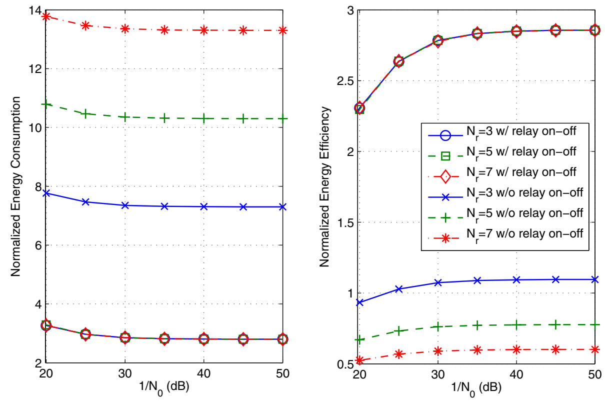

Fig. 1. Comparisons of normalized energy efficiency and normalized energy consumption with and without switching on/off relay mode under different N_r and $d_{\text{far}} = 900$ m.

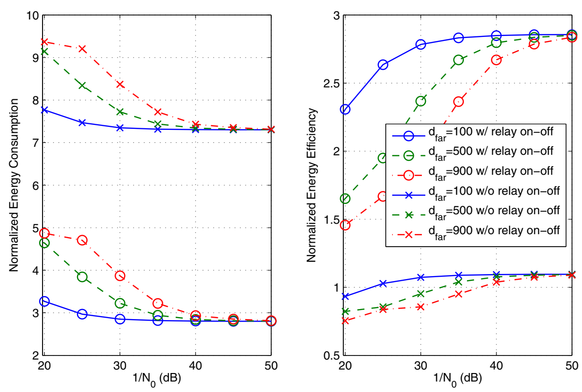

Fig. 2. Comparisons of normalized energy efficiency and normalized energy consumption with and without switching on/off relay mode under different d_{far} and $N_r = 3$.

increased, Fig. 1 demonstrates that the energy consumption rises and the energy efficiency decreases if unnecessary relays, which consume considerable energy, are not switched off. In contrast, the cooperative multicast network consumes less energy when only a subset of relays are active. Moreover, the cases of $N_r = 3$, 5, and 7 consume energy closely, because the energy consumption of unnecessary relays in each case is saved by optimally switching on/off modes for the relays.

Fig. 2 considers different d_{far} with $d_{\text{near}} = 0$ (with unit m) to compare the energy consumption and energy efficiency under different distributions of multicast destinations. Specifically, a smaller d_{far} results in a narrower distribution range of N_d multicast destinations $(0, d_{\text{far}}]$. Fig. 2 demonstrates that when the multicast destinations are distributed more densely with a smaller d_{far}, fewer active relays are required, leading to less energy consumption and better energy efficiency. This result is reasonable because fewer active relays are necessary to ensure a smaller coverage of multicast service when the multicast destinations are located nearby. Therefore, exploiting on/off relay mode effectively reduces network energy consumption, especially for a high density of multicast destinations.

Fig. 3 compares the time complexity of exhaustive search and that required by EESA to find the optimal solution of

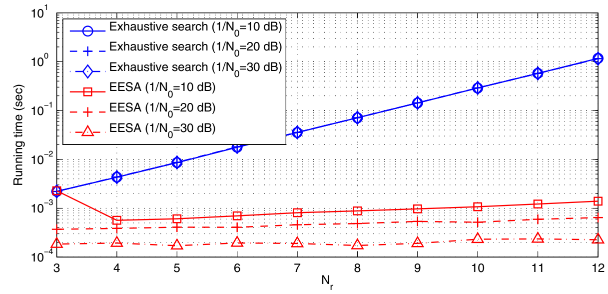

Fig. 3. Comparison of running time.

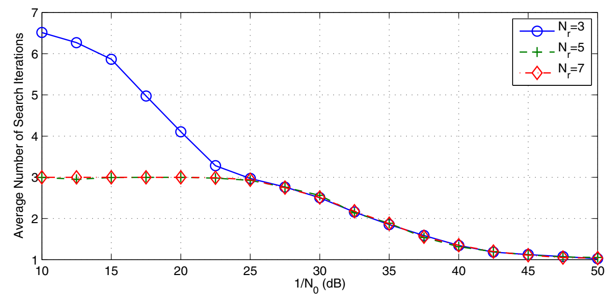

Fig. 4. Average number of search iterations required in EESA.

on/off relay mode and AM mode with different number of relays. The case with exhaustive search grows exponentially with the number of relays due to the exponential possibilities of on/off relays. In contrast, the case of EESA grows much slower as shown in Fig. 3, because EESA considers an efficient search order among the candidate solutions. Moreover, Figs. 3 and 4 demonstrate that EESA requires less time and fewer search iterations when $1/\mathcal{N}_0$ is larger. In this scenario, the candidate solutions with higher priority in the search order (with fewer active relays and higher AM modes) are more inclined to ensure multicast service. Therefore, EESA needs fewer iterations to find the optimal solution under a larger $1/\mathcal{N}_0$ in Fig. 4. In addition, Fig. 4 shows that the average number of iterations required in the cases of $N_r = 5$ and 7 are closed; this is because the number of relays in these two cases is sufficient large, so there always exists a best relay ensuring cooperative multicast service. Therefore, in these two cases EESA finds the optimal solution with a single active relay, which enjoys a high priority, by no more than three iterations. In contrast, in the case of $N_r = 3$ under a smaller $1/\mathcal{N}_0$, serving all multicast destinations requires multiple active relays with lower priority in the search order. As a result, more search iterations are needed to search for the optimal solution in this case.

Figs. 5–7 compares, respectively, the normalized energy efficiency, normalized energy consumption, and throughput among the cases with different objective functions: maximizing energy efficiency (Max. EE), maximizing throughput (Max. TP), and minimizing energy consumption (min. EC). The first objective function and its solution are discussed in Section III. The other two objective functions are $\max\{B_m\}$ and $\min\{EC\left(\overline{\lambda}\right)\}$, and their solutions are found by employing exhaustive search. Moreover, $N_r = 3$ is considered here. Figs.

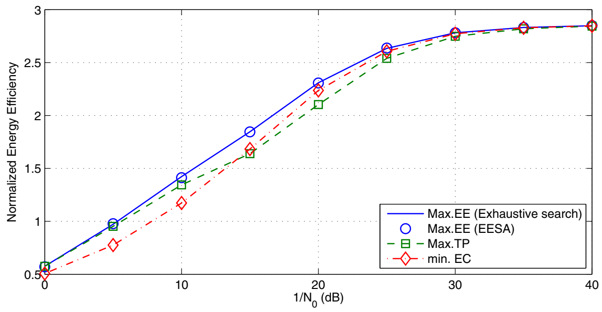

Fig. 5. Comparison of normalized energy efficiency.

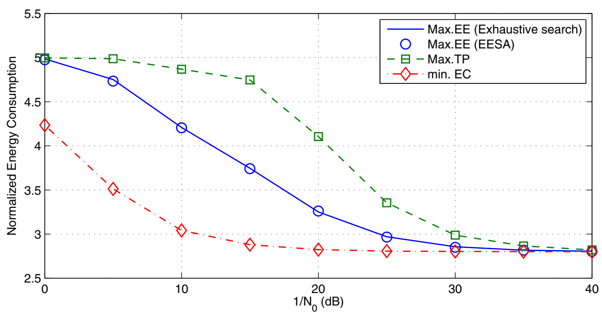

Fig. 6. Comparison of normalized energy consumption.

5–7 also shows that our proposed EESA is able to find the optimal solution, resulting in the same performance as the case with exhaustive search. From the comparison of normalized energy efficiency in Fig. 5, the case of Max. EE achieves the highest energy efficiency, because we jointly select on/off relay mode and AM mode to maximize energy efficiency. Moreover, the case of Max. TP outperforms the case of min. EC under $1/\mathcal{N}_0 \leq 15$ dB, while the case of min. EC performs better when $1/\mathcal{N}_0 > 15$ dB. This phenomenon can be explained by the results shown in Figs. 6 and 7. When $1/\mathcal{N}_0$ is smaller, the better throughput performed by Max. TP is able to improve the energy efficiency in Fig. 5. However, when $1/\mathcal{N}_0$ is larger, the additional energy consumption does not improve much throughput in the case of Max. TP, thereby reducing energy efficiency. As a result, we conclude that energy efficiency is a significant objective function to balance the trade-off between the energy consumption and throughput.

V. Conclusions

This paper proposed a joint selection of on/off relay mode and AM mode to maximize the energy efficiency for green cooperative multicast networks. In order to reduce the time complexity of searching for the optimal solution among exponential candidate solutions, we proposed the algorithm EESA based on an efficient search order. The simulation results demonstrate that switching on/off relay mode can significantly improve the energy efficiency for the cooperative multicast network. The results also demonstrate that the required time of EESA grows much slower as compared to the cases employing exhaustive search. In addition, from the comparisons among different objective functions, we conclude that maximizing

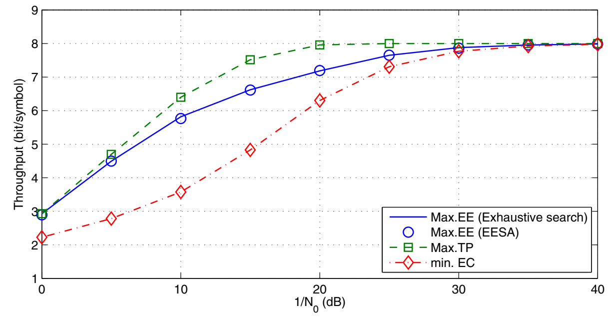

Fig. 7. Comparison of throughput.

energy efficiency is able to effectively balance the trade-off between energy consumption and throughput.

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