An Optimal Energy Efficient Cooperative Retransmission MAC Scheme in Wireless Networks

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***Abstract*—While the benefits of cooperative diversity have been well studied in the literature, cooperative MAC protocol design has also attracted much attention recently. In the single-relay Cooperative Automatic Repeat reQuest (C-ARQ) protocol, the best relay node is selected in a distributed manner by relays using different backoff time before packet retransmission. However, this relay selection scheme does not work efficiently in a dense network scenario, due to possible high collision probability among different contending relays. In this paper, we propose an optimized relay selection scheme to maximize system energy efficiency by reducing collision probability. The energy efficiency performance by the proposed optimal relay selection scheme is verified by simulations.**

I. INTRODUCTION

Cooperative communications are proposed as a distributed way to achieve space diversity via distributed terminals. The theory behind cooperation has been studied in depth, and significant improvement of system performance has been demonstrated in terms of throughput, network coverage and energy efficiency [1].

Increasing attention has recently been paid to cooperative Medium Access Control (MAC) design in distributed wireless networks [2]- [5]. Among them, a Cooperative Automatic Repeat reQuest protocol (C-ARQ) has been is proposed in [8] to deal with the three key issues on MAC layer. In single-relay C-ARQ, the relay nodes with successful reception of the direct transmission from source to destination will backoff different lengths of time before data retransmission, according to their instantaneous relay channel quality. Then, the relay node with best relay channel quality will be selected automatically to forward the data packet. The C-ARQ scheme can provide high performance enhancement compared with the non-cooperative scheme in a sparse network. However, Its performance would be remarkably degraded in dense networks because of the high probability of collisions in its relay selection procedure.

Moreover, the energy consumption aspect in a cooperative retransmission network has rarely been addressed in the literature. In our previous work [6], the energy consumption of the C-ARQ protocol has been investigated in a simplified three-node network. Its simulation results illustrated that the energy consumption of a whole network is distinctly affected by the location of the relay node. In fact, a cooperative MAC protocol can be further improved when energy consumption is taken into consideration.

Motivated by the above observations, an optimal energy efficient cooperative retransmission MAC protocol is proposed in this paper. Based on the C-ARQ protocol, an optimal relay selection scheme is presented to reduce collision probability in a dense network, aiming at maximizing energy efficiency of the relay node. Analysis and simulations are conducted to evaluate the performance enhancement of the proposed optimal scheme, in terms of packet delivery ratio and energy efficiency.

Furthermore, the optimal scheme here applies to a category of distributed path selection protocols based on different lengths of backoff time [7] before transmission. Hence, the optimization solution study is of great significance.

The rest of the paper is organized as follows. The system model is described in Sec. II. After that, the cooperative protocol is introduced in Sec. III. The optimization problem statement of the relay selection scheme is derived in Sec. IV, and the scheme performance is evaluated through simulations in Sec. V. Finally, the paper is concluded in Sec. VI.

II. SYSTEM MODEL AND ASSUMPTIONS

The network shown in Fig. 1 is taken as an example to illustrate the network topology and cooperation scenario. The network consists of a source node, S, a destination node, D, and several potential relay nodes, R_1, R_2, ..., R_n, randomly distributed around D [1].

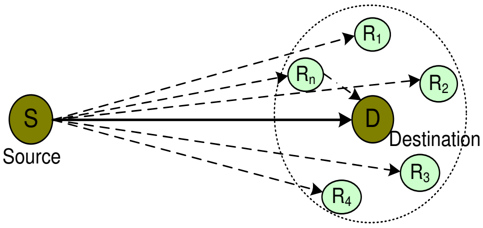

Fig. 1. System Model for Cooperative Transmission.

Each direct transmission starts from S, with the intended destination as D. If the direct transmission fails, the relay node which has received the packet successfully and has the best relay channel quality to D will be selected to forward the packet to D, following the cooperative retransmission protocol.

In this model, it is assumed that all nodes can hear each other. The distance between any relay node and D is negligible

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[1] This network topology is based on our previous work [6], where we have demonstrated that it is more energy efficient to use relay nodes closer to the destination in the context of cooperative retransmission network.

compared with the distance between S and D. The channels between every transmission pair, i.e., between S and D, S and each relay node R$_i$, as well as R$_i$ and D, are assumed to be independent of each other, hence full spatial diversity can be achieved by data retransmission over another/other channel(s). Moreover, we assume that channels are strongly temporally correlated, i.e., consecutive packets on the same channel are subjected to the same channel fading condition and hence identical packet error rate.

III. COOPERATIVE MAC PROTOCOL DESCRIPTION

The C-ARQ protocol is proposed based on the Distributed Coordination Function (DCF) scheme in WLANs, to deal with the three key issues on MAC layer, i.e., when to cooperate, whom to cooperate with and how to protect cooperative transmissions [8]. In this section, we first summarize the C-ARQ MAC protocol, and then introduce its relay selection algorithm in details in the second subsection.

A. Cooperative Automatic Repeat Request Scheme

The C-ARQ protocol procedure consists of two phases: direct transmission and cooperative retransmission. The cooperative retransmission only happens when the first direct transmission fails. It is briefly presented in the following about how the protocol works. More details can be found in [8].

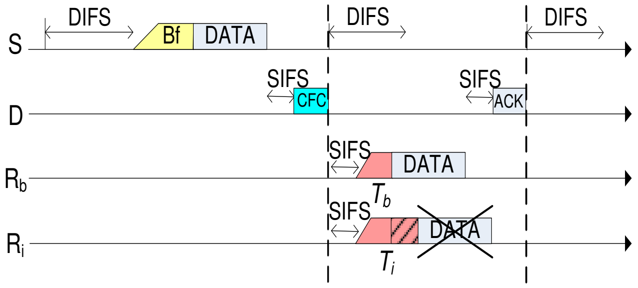

Fig. 2. C-ARQ Basic Scheme: Successful Cooperative Retransmission

As the first step, S sends out a DATA packet to its destination D following the original DCF basic access scheme. If and only if the data packet is received erroneously at D, D will broadcast a Call For Cooperation (CFC) packet to invite other nodes in the network to operate as relay nodes and at the same time to provide them the opportunity of measuring their respective relay channel quality. Only relay nodes that have decoded the packet sent by S correctly become relay candidates. According to the relay selection algorithm, the relay candidate with the best relay channel quality R$_b$, will first get channel access and forward its received packet to the destination. After detecting the data packet from R$_b$ on the channel, the other relay candidates will withdraw from their cooperation contention and discard their received packets. If D decodes the packet correctly after the best-relay-channel retransmission, D will return an ACK packet to S. Otherwise, the cooperative transmission fails. In this case, S will get access to the channel again after DIFS interval.

The message exchange sequence of the C-ARQ scheme with a successful cooperative retransmission is illustrated in Fig. 2.

B. Relay Selection Algorithm

The relay nodes in C-ARQ are selected in a distributed manner by using the instantaneous channel condition obtained through the CFC packet sent from D. After the cooperative phase starts, each relay candidate gets its backoff time of T_i according to its own relay channel condition.

1) backoff time function: In C-ARQ, the backoff time, T_i is defined as a function:

$$T_i = \left\lfloor \frac{SNR_{low}}{SNR_i} \frac{T_{up}}{slottime} \right\rfloor, \quad i = 1, 2, \dots, n \tag{1}$$

where SNR_i is the Signal-to-Noise Ratio (SNR) value in dB of the CFC packet received at R_i; SNR_{low} is the threshold of SNR_i for R_i to participate in cooperative retransmission; and n is the number of the relay nodes in the network. The value of SNR_{low} can be determined according to the specified Modulation and Coding Schemes (MCSs) at the physical layer. T_{up} in Eq. (1) is the upper bound of the backoff time for relay candidates. T_{up} in the basic C-ARQ scheme is set to be (DIFS-SIFS), in order to guarantee that the cooperative retransmission will not be interrupted by other nodes in the network. The granularity of T_i is specified to be *slottime* of the system in order to cover the propagation delay in the network.

2) backoff time look-up table: The mapping from SNR_i to T_i can also be implemented through a look-up table, as shown in Table I.

TABLE I
MAPPING FROM SNR TO BACKOFF TIME.

SNR_i	$[\vartheta_m, \infty)$	$[\vartheta_{m-1}, \vartheta_m)$	$[\vartheta_{m-2}, ...$	$(\vartheta_1, \vartheta_2)$
T_i	first slot	second slot	...	$DIFS - SIFS$

In Table. I, $\vartheta_j, j = 1, 2, ..., m$ are the threshold values of SNR_i to have different backoff time, and $\vartheta_1 \leq \vartheta_2 \leq ... \leq \vartheta_m$. ϑ_1 is the threshold value for the relay candidate to cooperate. Each relay candidate gets its backoff time T_i by looking up the above table using its measured SNR value of the CFC packet as index. It is obvious that the relay with highest SNR_i will get the first time slot and hence to transmit first.

The number of intervals divided among the SNR values in Table. I, m is determined by the durations of (DIFS-SIFS) and slottime. The longest backoff time available for the relays is set to $\left\lfloor \frac{DIFS-SIFS}{slottime} \right\rfloor$ slots to give priority to cooperative retransmission. The boundaries involved in this table, $\vartheta_i, i = 1, 2..., m$, can be optimized to maximize the required cooperative system performance. For instance, in a network with the 802.11g standard, the longest backoff time is three time slots. Hence, two threshold values, ϑ_1 and ϑ_2, need to be optimized. The optimization solution is dependent on given network scenarios, such as the wireless channel quality and the density of the relay nodes.

IV. Optimization Problem Statement

Let d denote the distance between the source node and a receiving node. We assume an average path loss that is proportional to d^a where a is the path loss coefficient. For brevity, we assume a Rayleigh fading channel with additive white Gaussian noise (AWGN) on top of path loss, although our analysis can be extended to other fading channels such as Rician or Nakagami.

The average received SNR at the receiver can be written as

$$\overline{\gamma} = \frac{G P_T (1-\alpha)}{d^\alpha N_0 W}, \tag{2}$$

where P_T is the RF transmission power; $(1-\alpha)$ accounts for the efficiency of the RF power amplifier, W is bandwidth in Hertz available for transmission; N_0 is the spectral power density of the Gaussian white noise at the receiver, and G is a constant that is defined by signal frequency, antenna gains, and other parameters.

The instantaneous received SNR under Rayleigh fading has an exponential distribution as:

$$f(\gamma) = 1/\overline{\gamma} e^{-\gamma/\overline{\gamma}}. \tag{3}$$

Substituting $\overline{\gamma}$ in Eq. (2) into Eq. (3), we can obtain:

$$f(\gamma) = \frac{d^\alpha N_0 W}{G P_T (1-\alpha)} e^{-\frac{\gamma d^\alpha N_0 W}{G P_T (1-\alpha)}} = C d^\alpha e^{-C d^\alpha \gamma}, \tag{4}$$

where $C = \frac{N_0 W}{G P_T (1-\alpha)}$.

A. Average Packet Error Rate

The exact closed-form PER in AWGN channels is difficult to obtain. To simplify the analysis, we rely on the following approximate PER expression from [9]:

$$PER_n(\gamma) \approx \begin{cases} 1 & \text{if } \gamma \le \gamma_n^{th} \\ \beta_n e^{-\kappa_n \gamma}, & \text{if } \gamma > \gamma_n^{th} \end{cases} \tag{5}$$

where n is the MCS index, and γ is the signal to noise ratio at the receiver. Parameters β_n, κ_n and γ_n^{th} are dependent on the specific MCS scheme and data packet length.

Given an average SNR value, the PER performance at the receiving node averaged over Rayleigh fading is given as:

$$\begin{aligned} \overline{PER}_r(\overline{\gamma}) &= \int_0^\infty PER(\gamma) f(\gamma)\, \mathrm{d}\gamma \\ &= \frac{\beta_n}{1+\kappa_n \overline{\gamma}} e^{-\gamma_n^{th}(\kappa_n + 1/\overline{\gamma})} + \left(1 - e^{-\gamma_n^{th}/\overline{\gamma}}\right). \end{aligned} \tag{6}$$

Since all the relays nodes are close to the destination, and the distance between them is negligible compared with the distance from source to destination, we assume the average SNR is the same at all the receiving nodes in the direct transmission phase. Therefore, the *average packet error rate*, denoted as $\overline{PER}_r$, is also the same at the destination and other relay nodes. Substituting Eq. (2) into Eq. (6), we have:

$$\overline{PER}_r = \frac{\beta_n C d^\alpha}{C d^\alpha + \kappa_n} e^{-\gamma_n^{th}(\kappa_n + C d^\alpha)} + \left(1 - e^{-\gamma_n^{th} C d^\alpha}\right). \tag{7}$$

Assume further that there are N nodes in the network, and denote the number of nodes that correctly decode the packet as M. Since the channels from the source to different relays are independent, the events that one node successfully receives a packet are independent of each other. Thus, the number of successful nodes is actually subject to a binomial distribution. The probability that M nodes correctly decode the packet is

$$P(M) = \binom{N}{M} \left[1 - \overline{PER}_r\right]^M \left[\overline{PER}_r\right]^{N-M}. \tag{8}$$

B. Conditional Cooperation Retransmission Probability

In the cooperative retransmission phase, the M relay nodes with successful reception of the data packet will first measure the received signal strength of the CFC packet, denoted as $\gamma_i, i = 1, 2..., M$, then contend for channel access using different backoff time T_i according to γ_i. Here, γ_i represents the instantaneous channel condition from relay to destination and follows a similar distribution function in Eq. (4). The path loss is neglected in this case because of the short distance between relay nodes and D. For convenience, we sort γ_i in the descending order, as $\gamma_1 \ge \gamma_2 \ge \gamma_3 ... \ge \gamma_M$.

The probability of the cooperative retransmission conditioned on the direct transmission failure, denoted as P_{coop}, is the probability that there is at least one relay node that will transmit before DIFS-SIFS timeout after an unsuccessful direct transmission. Probability P_{coop} is equal to the probability of the event that the relay node with the best relay channel quality has higher SNR value than the threshold value, ϑ_1, and hence transmit before DIFS-SIFS. Considering the independence of the channels from the source to different relays, P_{coop} can be calculated as:

$$\begin{aligned} P_{coop}(\vartheta_1, M) &= P\{\gamma_1 > \vartheta_1\} = 1 - P\{\gamma_1 \le \vartheta_1\} \\ &= 1 - P\{\gamma_i \le \vartheta_1, i = 1, 2, ..., M\} \\ &= 1 - \prod_{i=1}^{M} \int_0^{\vartheta_1} C e^{-C\gamma_i} d\gamma_i \\ &= 1 - \left(1 - e^{-C\vartheta_1}\right)^M. \end{aligned} \tag{9}$$

Averaging P_{coop} over the number of successful relays leads to:

$$\overline{P}_{coop}(\vartheta_1) = \sum_{i=0}^{M} P(M) P_{col}(\vartheta_1, M). \tag{10}$$

C. Collision Probability among Different Relays

Collision will happen when γ_1 and γ_2 have similar values, which leads to two relays sharing the same backoff time. Therefore, the collision probability, P_{col}, can be written as:

$$P_{col} = \sum_{j=1}^{m} P\{\gamma_1, \gamma_2 \in [\vartheta_j, \vartheta_{j+1})\}, \tag{11}$$

where $\vartheta_{m+1} = \infty$. To calculate P_{col}, we have:

$$\begin{aligned} P\{\gamma_1, \gamma_2 \in [\vartheta_j, \vartheta_{j+1})\} &= P\{\gamma_1, \gamma_2 < \vartheta_{j+1}\} - P\{\gamma_1 < \vartheta_j\} \\ &\quad - P\{\gamma_2 < \vartheta_j, \vartheta_j \le \gamma_1 < \vartheta_{j+1}\}. \end{aligned} \tag{12}$$

In the following, we derive the three items on the right side of Eq. (12) step by step. As defined, γ_1 and γ_2 are the maximal and the second maximal values of the received signal strengths at all the relays, respectively. Hence, $P\left\{\gamma_1, \gamma_2 < \vartheta_{j+1}\right\}$ is equivalent to $P\left\{\gamma_1 < \vartheta_{j+1}\right\}$, and can be obtained as:

$$\begin{aligned} P\left\{\gamma_1, \gamma_2 < \vartheta_{j+1}\right\} &= P\left\{\gamma_1 < \vartheta_{j+1}\right\} \\ &= C^M \prod_{i=1}^{M} \int_0^{\vartheta_{j+1}} e^{-C\gamma_i} d\gamma_i \\ &= \left(1 - e^{-C\vartheta_{j+1}}\right)^M . \end{aligned} \tag{13}$$

Similarly, $P\left\{\gamma_1 < \vartheta_j\right\}$ can be easily obtained. Then, $P\left\{\gamma_2 \le \vartheta_j, \vartheta_j \le \gamma_1 < \vartheta_{j+1}\right\}$ can be calculated as:

$$\begin{aligned} &P\left\{\vartheta_j \le \gamma_1 < \vartheta_{j+1}, \gamma_i \le \vartheta_j, i = 2, ..., M, \right\} \\ &= \binom{N}{1} \int_{\vartheta_j}^{\vartheta_{j+1}} C e^{-C\gamma_i} d\gamma_i \prod_{i=1}^{M-1} \int_0^{\vartheta_j} C e^{-C\gamma_i} d\gamma_i \\ &= \binom{N}{1} \left(e^{-C\vartheta_j} - e^{-C\vartheta_{j+1}}\right) \left(1 - e^{-C\vartheta_j}\right)^{M-1} . \end{aligned} \tag{14}$$

In this way, P_{col} can be expressed as a function of distance d, the number of relays M, number of thresholds m, threshold values $\vartheta_j, j = 1, 2, .., m$.

Averaging P_{col} over the number of successful relays, we have:

$$\begin{aligned} \overline{P}_{col}(\vartheta_j, m) &= \sum_{i=0}^{M} P(M) P_{col}(\vartheta_j, m, M) \\ &= \sum_{i=0}^{M} P(M) \left(\sum_{j=1}^{m} P\left\{\gamma_1, \gamma_2 \in [\vartheta_j, \vartheta_{j+1})\right\} \right) . \end{aligned} \tag{15}$$

Thus, the closed-form expression of the average collision probability among different relay node, $\overline{P}_{col}$, is derived as a function of the threshold values $\vartheta_j, j = 1, 2..., m$.

D. Energy Consumption Performance Analysis

The performance of the cooperative retransmission protocol is analyzed in terms of saturation throughput and Packet Delivery Rate (PDR) at the MAC layer in this subsection.

The PDR of the cooperative scheme is the sum of the packet successful rate in the direct phase and the additional successful probability in the cooperative retransmission phase. Note that in our analysis, no data corruption is assumed on the relay channels from R$_i$ to D due to short distances. That is, a failure of the cooperative retransmission is only caused by the collision among different relays due to the imperfect relay selection scheme.

$$PDR_c = 1 - \overline{PER}_r + \overline{PER}_r \overline{P_{coop}} (1 - \overline{P_{col}}). \tag{16}$$

The energy efficiency at the relay node, denoted by η, is defined as the successfully delivered information bits by each consumed joule of energy, and can be written as:

$$\eta = \frac{E[\psi]}{E[J]}, \tag{17}$$

where $E[\psi]$ is the additional number of payload information bits successfully transmitted by the relay nodes during cooperative retransmissions in a virtual time slot, i.e., the time interval between two consecutive packet transmissions initiated by S in this study, and $E[J]$ is the expected energy consumption of the relay nodes during one virtual time slot. It is obvious that the higher the value of η, the more energy efficient the evaluated system.

For our proposed scheme, $E[\psi]$ and $E[D]$ are expressed as follows. Here, the energy consumption of the relay nodes in the idle and receiving modes are neglected in our analysis.

$$E[\psi] = \overline{PER}_r \overline{P_{coop}} (1 - \overline{P_{col}}) L; \tag{18}$$

$$E[J] = \sum_{\omega=0}^{N} P(\omega) \omega P_T T_{DATA}, \tag{19}$$

where L is the payload length in bits; T_{DATA} is the transmission time for the DATA packet in Fig. 2; ω is the number of simultaneous transmitting relay node and $P(\omega)$ is the probability of ω simultaneous transmitting relay nodes.

The probability that $(\omega - 1)$ relay nodes share the same backoff time with the relay node that has the best relay channel quality, denoted as $P_M(\omega)$, can be calculated as:

$$P_M(\omega) = \sum_{j=1}^{m} P\left\{\gamma_1, \gamma_2, ...\gamma_\omega \in [\vartheta_j, \vartheta_{j+1})\right\}, \tag{20}$$

which can be obtained in a similar way to Eq. (11).

Averaging $P_M(\omega)$ over the number of successful relays, we have $P(\omega)$:

$$P(\omega) = \sum_{i=0}^{M} P(M) P_M(\omega). \tag{21}$$

Finally, the energy efficiency at the relay node of the cooperative retransmission scheme, η, can be obtained by taking Eqs. (20) and (21) into Eq. (19), and then substituting Eqs. (18) and (19) into Eq. (17).

E. Optimization Statement

Based on the analysis in the preceding subsections, the average energy efficiency is dependent on the threshold values $\vartheta_j, j = 1, 2..., m$ with given noise power, $N_0 W$, the distance from S to D, d, the number of relay nodes, N, and so on. With given relay topology in the network and channel conditions, the throughput can be expressed as a function of $\vartheta_j, j = 1, 2..., m$, and optimal values of ϑ_j should be derived to maximize the system energy efficiency. The optimization problem can be formulated as follows:

$$\begin{aligned} &\texttt{Maximize} \left\{\eta(\vartheta_j, m)\right\}, j = 1, 2, ..., m \\ &\texttt{subject to} : \vartheta_{j+1} - \vartheta_j \ge 0, j = 1, 2, ..., m, \\ &m = \left\lfloor \frac{DIFS - SIFS}{slottime} \right\rfloor . \end{aligned} \tag{22}$$

As mentioned in Sec. III, the number of threshold values, m, is determined by the durations of $(DIFS - SIFS)$ and slottime. In our study, we use the 802.11g system for illustration,

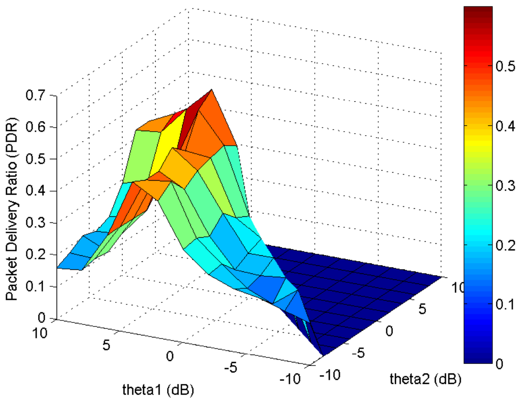

Fig. 3. PDR with Different Threshold Values (E_b/N_0= 0 dB).

and two parameters, ϑ_1 and ϑ_2, will to be tuned to optimize system energy efficiency.

V. SIMULATIONS AND NUMERICAL RESULTS

To evaluate the performance of the proposed scheme, we have implemented the original C-ARQ protocol in [8] and the enhanced version with the optimal energy efficient solution in MATLAB for comparision.

The simulation parameters are set up according to the 802.11g standard, as listed in Table II. S and D are placed 300 meters apart from each other. Fifty relay nodes are placed randomly within a radius of 30 meters around the destination node. The channels between each transmission pair are implemented as independent Rayleigh fading channels. QPSK and Convolutional Code (CC) 1/2 are adopted, with the corresponding β_n, κ_n and γ_n^{th} from Eq. (5) as 7.2×10^3, 5.3, and 2.0 dB, respectively.

TABLE II
SIMULATION PARAMETERS.

MCS Scheme	QPSK/ CC 1/2	DATA length	500 Bytes
ACK length	14 Bytes	CFC length	14 Bytes
MPDU header	24 Bytes	DIFS	34 μs
PHY header	20 μs	SIFS	16 μs
Datarate	34 μs	Slottime	9 μs
Basic datarate	6 Mbps	CW_{min}	15
RF efficiency α	0.5	Path loss exponent γ	4
P_T	1400 mW	W	20 MHz

Fig. 3 illustrates the influence of different threshold values on the packet delivery ratio of the cooperative retransmission protocol. It is obvious that the performance of the cooperative scheme with high density of relay nodes is highly affected by the different threshold values. The network performance can be improved significantly by reducing collision probability through the optimal threshold values.

The energy efficiency improvement by using the optimized relay scheme compared with the original C-ARQ scheme under different channel conditions is shown in Fig. 4. The optimal values of the threshold SNR are obtained through the analysis in Sec. IV. It can be observed that the optimal relay scheme keeps optimal energy efficiency under all different channel conditions, while the original cooperative retransmission shows its benefits mainly when the channel is in poor conditions. The reason is that when the channel condition gets better, a lot of energy is wasted when collisions happen among multiple relays with the original C-ARQ scheme.

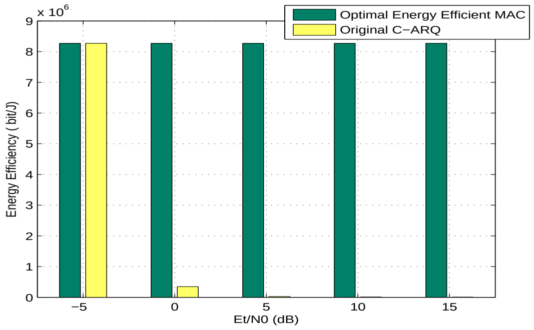

Fig. 4. Energy Efficiency Performance Comparision (SNR_{low}=2.0 dB).

VI. CONCLUSIONS

Energy consumption is a very important aspect to evaluate a cooperative transmission scheme. In this paper, we presented a complete analysis of the C-ARQ protocol performance with impairment resulted from collision. Thereby, an optimized relay selection scheme is proposed to maximize system energy efficiency. Numerical results have shown that the proposed optimal scheme is much more energy efficient compared with the original C-ARQ protocol under different channel conditions. Furthermore, the proposed optimization scheme can also be adopted in other protocols with similar problems.

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