Energy-Efficiency Evaluation of a Medium Access Control Protocol for Cooperative ARQ

J. Alonso-Zarate*, E. Stavrou†, A. Stamou†, P. Angelidis†, L. Alonso‡, and C. Verikoukis*
*Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Castelldefels, Barcelona, Spain
{jesus.alonso, cveri}@cttc.es
†Department of Informatics and Telecommunications Engineering, University of Western Macedonia
{stavroueirini, stamouad}@gmail.com, paggelidis@uowm.gr
‡Dept. of Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC), Castelldefels, Barcelona, Spain
luisg@tsc.upc.edu

Abstract—**We present in this paper the evaluation of the energy consumption of PRCSMA, an 802.11-based medium access control protocol designed to coordinate the retransmissions from the relays in a wireless network implementing a Cooperative Automatic Retransmission Request (C-ARQ) scheme. A comparison in terms of energy efficiency with non-cooperative ARQ schemes (retransmissions performed only from the source) and with ideal C-ARQ (with perfect scheduling among the relays) is included in this paper. The main results show the conditions under which a C-ARQ scheme with PRCSMA outperforms, in terms of energy efficiency, non-cooperative ARQ schemes and also show that the overhead of the MAC layer cannot be neglected in order to accurately evaluate the performance of a C-ARQ scheme.**

I. INTRODUCTION

The past years have witnessed the unprecedented market penetration of wireless communication devices based on the IEEE 802.11 Standard. This popularization of Wireless Local Area Networks (WLANs) has motivated the research community to intensively work over the time to improve and optimize their performance in order to increase their capacity, reduce delays, latencies, and jitters, and provide users with some service guarantees, i.e., Quality of Service. This effort comes as a response to the increasing demand for the transmission of multimedia contents, video streaming, and more demanding applications. However, a new dramatic reality is rising: the importance of energy efficiency. As devices become more sophisticated, their energy budget is increasing, and thus mobile devices are becoming strongly tied to battery power recharging, which limits the lifetime of the terminals and, consequently, the lifetime of the whole network. Therefore, it is important to design novel communication protocols that take into account the importance of an efficient energy consumption behavior, and evaluate the energy-efficiency of existing protocols to evaluate its suitability for certain applications.

In this paper, we focus on the Medium Access Control (MAC) layer, where there have been already some works evaluating the energy efficiency of different protocols. The Distributed Coordination Function (DCF) of the IEEE 802.11 Standard has been evaluated from an energy-efficient point of view in different works [1]-[3]. In each of these papers, the energy consumption models have been incrementally improved by considering different access modes and including or not inter frame silence (IFS) periods. In [4], [5], and [6], the energy efficiency of the DCF has been compared to that of a novel protocol, named S-MAC, which is based on DCF but includes an energy-efficient sleep mode. An energy performance evaluation of the 802.11e Hybrid Coordination Function (HCF) and Enhanced DCF (EDCF) with basic and COLAV access mode protocols has been presented in [7]. An important conclusion that can be drawn from these works based on the 802.11 is that the adoption of an accurate energy consumption model plays an important role in the energy-efficiency evaluation of a MAC protocol.

Having this in mind, we present in this paper the energy performance evaluation of the Persistent Relay Carrier Sensing Multiple Access (PRCSMA) protocol [8]. PRCSMA is a MAC protocol designed to coordinate the retransmissions from the relays in Cooperative Automatic Retransmission Request (C-ARQ) schemes. The main idea behind C-ARQ is to exploit the broadcast nature of the wireless channel in the following manner: whenever a destination receives a data packet with unrecoverable errors, it can request retransmissions from any of the users which overheard the original transmission, which can act as spontaneous relays. Therefore, cooperative diversity gains can be attained [9]. PRCSMA is a MAC protocol devoted to coordinate the retransmission from the relays in the case that more than one user is willing to cooperate. PRCSMA is based on the IEEE 802.11 MAC protocol, but modified to meet the requirements of an efficient MAC protocol for C-ARQ. The performance analyses of PRCSMA that can be found in [8] and [10] are based on throughput and delay. However, there is yet no energy performance evaluation of the protocol. This is the main motivation for the work presented in this paper.

The main contributions of this paper are:

1) The adoption of an accurate energy-consumption model for PRCSMA, for both the collision avoidance and basic access modes.

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2) A comprehensive simulation-based performance evaluation of PRCSMA from the energy-efficient point of view. To do so, we have considered all the possible radio states (transmit, receive and idle) and we have included the backoff and collision delays as well as inter frame spacing (IFS) in the model. We consider two different cases with either always-on relays or with energy-efficient relays capable of entering into sleep mode when not involved in the communications.
3) A comparison of the energy efficiency of a C-ARQ with PRCSMA to that of an ideal C-ARQ with perfect scheduling system, i.e., without contention among the relays to get access to the channel to retransmit. This comparison explicitly evaluates the energy consumption overhead generated by an actual MAC protocol and demonstrates that its overhead must not be neglected in order to evaluate the actual performance of any C-ARQ scheme.

The remainder of the paper is organized as follows. A brief overview of PRCSMA is presented in Section II. Then, the system model used to carry out the energy-efficiency evaluation is described in Section III. Simulation results are discussed in Section IV and, finally, Section IV concludes the paper.

II. PRCSMA OVERVIEW

PRCSMA is a protocol designed to coordinate the retransmission of the relays in a C-ARQ scheme. Whenever a destination receives a data packet with errors, it broadcasts a Call for Cooperation (CFC) packet and a *cooperation phase* is initiated. All the users which overheard the original transmission from the source (without errors) and receive this CFC packet become active relays and contend to get access to the channel in order to assist the destination. The operation of PRCSMA is essentially based on the rules of the IEEE 802.11 MAC protocol, except for the following modifications:

1) The relays perform a backoff upon the reception of the CFC broadcast by the destination asking for cooperation in order to avoid a certain collision among all the relays willing to cooperate.
2) The relays do not expect any ACK for each retransmission as they are not the original source of the transmitted packet. Therefore, the overhead associated to the retransmissions can be reduced.
3) The Virtual Carrier Sensing function of the protocol is modified to take into account the duration of cooperation phases in order to properly update the value of the Network Allocation Vector (NAV).

A cooperation phase is finished whenever the destination is able to decode the original packet and transmits broadcasts an ACK packet. In the case that a certain time-out time elapses and the packet has not been recovered, it can be discarded for the benefit of the backlogged data.

As in the 802.11 MAC protocol, in PRCSMA both the basic access and the collision avoidance access (with RTS and CTS handshake) are considered for the protocol operation.

Due to space constraints, it has not been possible to include in this paper a more comprehensive description of PRCSMA. The interested reader is referred to [8] and [10] for an exhaustive definition of the protocol operation.

III. SYSTEM MODEL

In this section we specify the scenario, channel model and energy consumption model used to carry out the energy-efficiency evaluation of PRCSMA.

A. Scenario

We consider a wireless network composed of a source, and a distant group of one fixed destination and a constant number n of potential helpers or relays. Note that this scenario represents the typical scenario formed by a base station or access point and the users of the network. The destination station broadcasts a CFC packet upon the reception of a data packet with unrecoverable errors a ***cooperation phase*** is initiated. All the potential relays that received the original data without errors become active relays upon the reception of the CFC from the destination. PRCSMA is used at the MAC layer to execute a C-ARQ scheme and attempt to recover the data received with errors.

B. Channel Model and Rate Adaptation

We assume that transmissions in the control plane are error-free, and thus ACK and CFC packets are always received without errors. This is justified by to the short bit-length of control packets and the fact that they are always transmitted at the lowest available transmission rate (most robust transmissions). For data transmissions, a Non Line-of-Sight (NLOS) block-fading Rayleigh channel has been considered. In particular, block-fading means that the channel quality is assumed to remain constant for at least the transmission of a whole single packet. Therefore, the packet error probability can be considered constant and depends on the average Signal to Noise Ratio (SNR) in the link from the transmitter to the receiver.

P_{RD} is the packet error probability in the link between the relays and the destination. P_{SD} is the packet error probability in the links between the source and the destination, and between the source and the relays. Recall that since we are considering a scenario with a distant source (e.g., a base station in a cellular network) all the users (destination and relays) perceive, in average, the same channel statistics, but with different and independent realizations. It is important to note that the number of active relays is inversely proportional to the value of P_{SD}, and therefore, an error occurred when the channel quality is good leads to heavy relay contention (high number of active relays). On the other hand, high values of P_{SD} lead to higher probability of error, but also to lower number of active relays, and thus lower contention.

The available transmission rate between a transmitter and a receiver is set depending on the average SNR, which in its turn, depends on the relative distance between transmitter and receiver. Therefore, the transmission rate between the source and the destination is considered to be lower than the transmission rates available between the relays and the destination. For this reason, retransmissions from the source are costly in terms of channel usage and a C-ARQ scheme can help in improving the performance of the network and extending the coverage of the source to be able to intercommunicate with distant stations.

C. Energy Consumption Model

Four radio operation modes are considered:

1) ***Transmitting mode***, when the radio is transmitting data packets or control frames,
2) ***Receiving mode***, when the radio is receiving and attempting to decode incoming packets,
3) ***Idle mode***, when radio is sensing the channel, and
4) ***Sleeping mode***, when radio is in low power, and it is not able to receive or transmit.

The power consumptions associated to each mode are P_T, P_R, P_I, and P_S, respectively. The energy consumption E is calculated as $E = Pt$ where, P is the power and t the time.

In order to compute the total energy consumption of the system we consider two different types of relays:

1) ***Always-on relays***, assuming that the non-active relays remain on (idle mode) for the cooperation phase, and
2) ***Energy-efficient relays***, assuming that non-active relays go to sleep mode for the duration of the current a cooperation phase and wake up right after the transmission of the ACK from the destination.

IV. PERFORMANCE EVALUATION

Computer simulations based on MATLAB have been carried out to evaluate the energy efficiency of PRCSMA. Before presenting the results, be define in the next subsection the three considered case studies.

A. Case Studies

We consider the following case studies depending on the ARQ scheme executed in the system:

1) Non-cooperative ARQ scheme where retransmissions are requested directly, and only, from the source. Retransmissions are performed one after another, sequentially in time, and each retransmission is acknowledged, if received without errors, by the destination.
2) C-ARQ scheme where an ideal scheduling is attained among the relays, i.e., no backoff periods and no collisions. In this case, each retransmission does not have to be acknowledged by the destination but a final ACK/NACK packet is transmitted at the end of the cooperation phase.
3) C-ARQ scheme where the relays execute PRCSMA (both with the basic and the collision avoidance (COLAV) access modes, i.e., with RTS-CTS handshake).

For each of these case studies, we consider the case of having always-on relays (scenario 1), and energy-efficient relays (scenario 2). Therefore, we consider a total of six cooperative cases.

TABLE I
SIMULATION PARAMETERS

Parameter	**Value**	**Parameter**	**Value**
SIFS, SlotTime	10 μs	CW_{min},CW_{MAX}	32
MAC header	34 bytes	PHY preamble	96 μs
ACK, CFC	14 bytes	DIFS	50 μs
RTS	20 bytes	CTS	14 bytes

For the non-cooperative networks, we consider two different cases:

1) *No Cooperation(1)*: traditional ARQ with energy-efficient relays, i.e., the relays are always in off state, and, therefore, the predominant considered energy expenditure is that of the source and the destination.
2) *No Cooperation(2)*: traditional ARQ with always-on relays. Note that in this case, the relays just overhear the transmissions but they never cooperate. It is worth mentioning that unless the network has dedicated relays, this is the most realistic case, as potential relays are other users in the network, which are always-on. For this reason, this will be used as the main benchmark reference scheme.

B. System Parameters

Considering the specifications of Aironet's PC4800 PCMCA (Personal Computer Memory Card International Association) NIC (Network Interface Card) [12], we have that $P_T = 1900 mW$, $P_R = P_I = 1340 mW$, and $P_S = 75 mW$. Indeed, these values match with the experimental results reported by Feeney [2], showing that the energy consumption of overhearing a frame, staying idle, or sensing the channel are only marginally different from the energy consumption of receiving a frame.

We have considered that all transmissions at the control plane are error-free and they are performed at 6 Mbps. Recall that this is the most robust modulation scheme of the IEEE 802.11g [13]. Regarding the data plane, we have assumed that the relays always transmit at the most aggressive coding scheme defined in 802.11g, i.e., at 54 Mbps, while the source (distant source) transmits data at 6 Mbps.

The length of data packets has been fixed to 1500 bytes, which is the size that better represents the size of WLAN traffic [14].

The rest of the simulation parameters are summarized in Table I, and they have been defined according to the recommended values in the IEEE 802.11g [13].

C. Results

As in [15], we define the ***energy efficiency*** of a protocol as the ratio between total amount of successfully transmitted data bits and the total energy expenditure in a simulation. Therefore, this measure has units of *bits/Joule*.

Figure 1 shows the results for $P_{RD} = 0.1$, i.e., good channel conditions between the relays and the destination, and one single potential relay ($n = 1$). All the cooperative schemes behave similarly. Note that since there is just one potential

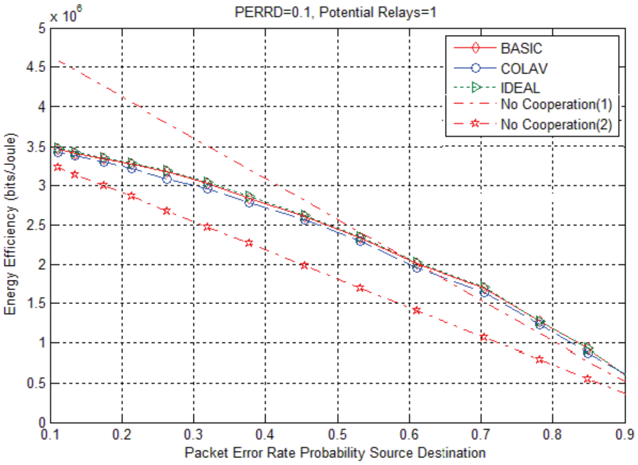

Fig. 1. Energy Efficiency for $p_{RD} = 0.1$ and $n = 1$

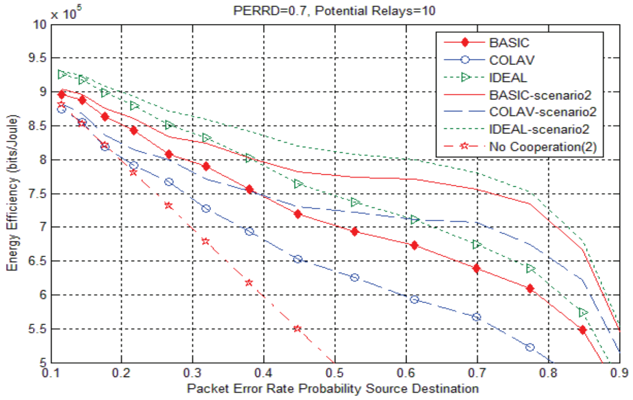

Fig. 2. Energy Efficiency for $p_{RD} = 0.7$ and $n = 10$

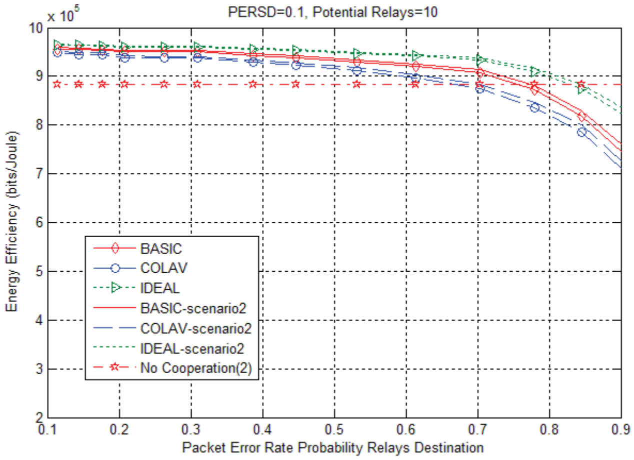

Fig. 3. Energy Efficiency for $p_{SD} = 0.1$ and $n = 10$

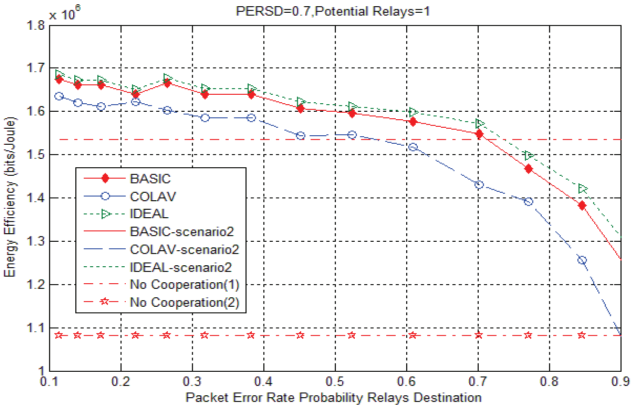

Fig. 4. Energy Efficiency for $p_{SD} = 0.7$ and $n = 1$

relay, there is no contention and thus basic and ideal lines almost coincide, and the collision avoidance method just adds some overhead. When compared to the non-cooperative ARQ scenarios, we get different results depending on whether we consider case 1 (energy-efficient relays) or case 2 (always-on relays). When compared to the case 2 (more realistic), we wee that a C-ARQ can improve the energy-efficiency of the communications. The higher the packet error probability in the link between source and destination, the higher the probability that retransmissions are requested is, and thus the more relevant the benefits of the PRCSMA scheme become in terms of energy efficiency. Note, however, than when the value of p_{SD} becomes very high, then the probability that there are no active relays is also high, and thus the overall performance drops again. The non-cooperative case 1 (energy-efficient relays) attains the highest energy performance when the packet error probability is low. However, as the value of p_{SD} becomes greater than 0.5, the C-ARQ is able to subtly outperform the non-cooperative approach.

In order to avoid redundancy, we do not include here the results for greater number of potential relays as the obtained results are very similar to those discussed here. It is worth mentioning though that as the number of potential relays increases, the contention process (collisions and idle times due to backoff) reduces the efficiency of the cooperative approaches. This translates into moving away the curve for the cooperative cases from case 1 and approaching them to case 2, but still attaining better performance.

We focus now on the case when the packet error probability between the relays and the destination is high, in particular $p_{RD} = 0.7$ and $n = 10$. The energy efficiencies of the different simulated networks are depicted in Figure 2. Note that the increase in the number of potential relays in the system reduces the energy efficiency when compared to the results shown in Figure 1. Under these conditions, the average number of required retransmissions from the relays is greater than in the previous case due to the higher probability of packet error in a retransmission. In this case, the effects of the contention process among the relays become more remarkable and there is a clear impact on the energy-efficiency of the system. This can be simply observed by the fact that, in this case, there is a clear difference between the ideal scheduling and the two different access methods of PRCSMA.

The first observation is that despite the higher probability of packet error in a retransmission from the relays, all the PRCSMA schemes considered outperform the non-cooperative ARQ (with always-on relays) in all cases. The reason for that is that despite the higher probability of error in the link between the relays and the destination, the cost of a failed retransmission is much lower in terms of energy from the relays than from the source.

So far, we have fixed the value of p_{RD} and evaluated the system as a function of p_{SD}. We do the complementary exercise now. In Figure 3, the energy efficiency of the network is evaluated as a function of the value of p_{RD} for a given value of $p_{SD} = 0.1$ (good channel conditions between source and relays and destination).

Results show that all C-ARQ schemes outperform the non-cooperative ARQ (scenario2) scheme in all cases when the channel conditions between the relays and the destination are good. However, above a certain threshold (whose vale depends on the type of PRCSMA access), the non-cooperative ARQ yields better energy performance, as the benefits attained by the faster retransmission from the relays do not pay off the overhead energy expenditure. Above this threshold, the increasing number of required retransmissions also extends the duration of the cooperation phase, leading to greater probability of having collisions and wasted time in idle periods. It has to be emphasized that idealizing the MAC overhead leads to misleading conclusions. Note that this turning point (threshold) shifts from $p_{RD} = 0.8$ to $p_{RD} = 0.65$ if instead of assuming perfect scheduling we consider the collision avoidance mode of PRCSMA.

For completeness, we show in Figure 4 the case when $p_{SD} = 0.7$ and $n = 1$. These results reinforce the previous discussion, showing the importance of the MAC overhead in an actual energy-efficiency performance evaluation and the improved performance of C-ARQ over non-cooperative ARQ in terms of energy-efficiency. It is worth observing in this figure that all the C-ARQ schemes outperform the non-cooperative ARQ scheme even in the case of having energy-efficient relays when the value of p_{RD} is lower than 0.6, which might be the case of practical situation.

V. CONCLUSIONS AND FUTURE WORK

We have evaluated in this paper the energy efficiency of a wireless network executing a C-ARQ scheme to recover data packets received with errors. We have focused on the energy consumption evaluation of a MAC protocol for C-ARQ named PRCSMA. This protocol is based on the IEEE 802.11 and constitutes a practical protocol to be implemented in real networks. Computer based simulations implementing a realistic energy consumption model show that a C-ARQ scheme can outperform non-cooperative ARQ scheme even in the case that the channel conditions between the relays and the destination are worse, to a certain extent, than those between the source and the destination. In addition, results show that the MAC protocol plays a critical role in the evaluation of any C-ARQ scheme under specific network conditions and, therefore, the idealization of the contention time can lead to wrong conclusions regarding the energy efficiency of C-ARQ. Therefore, an efficient MAC protocol is necessary to efficiently coordinate the relay retransmissions in a C-ARQ scheme so that a performance close to the ideal perfect scheduling can be attained.

Future work will be aimed at further detailing the energy consumption model by including transitional steps (from transmission to reception) and theoretical deriving the existing trade-off between throughput, delay, and energy.

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