Performance Evaluation of a Medium Access Control Protocol for a Distributed ARQ Scheme in Cooperative Wireless Networks

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Abstract: A performance evaluation of a medium access control protocol for a distributed ARQ scheme in cooperative wireless networks is presented in this paper. The protocol under evaluation is the Persistent Relay Carrier Sensing Multiple Access protocol (PRCSMA). The protocol was designed to be easily integrated in standard IEEE 802.11 networks in order to increase their performance and to extend coverage. The main goals of this paper are to present and to discuss the performance evaluation of the PRCSMA under different network configurations. Computer simulations demonstrate the robustness of the protocol under different scenarios.

Keywords: Performance evaluation, MAC, distributed ARQ, PRCSMA.

1. Introduction

The performance of wireless communication networks may be improved by exploiting the broadcast nature of the radio channel. The key idea is to enable the cooperation among users whenever a transmission fails, based on the observation that, in a wireless network, any transmission can be overheard by all the stations within a certain transmission range of the transmitting station. Therefore, once a message is transmitted, all the stations in the transmission range of the source become potential helpers for the communication link. These stations are referred to as the relays, and their spatial distribution may allow for the exploitation of either space or time diversity. The improvement induced by cooperative communications in wireless networks can be attained in terms of higher transmission rate, lower transmission delay, more efficient power consumption, or even increased coverage range, among others.

The fundamental theory behind the concept of cooperation has been deeply studied among researchers during the past years [1]-[3]. Currently, it is one of the hottest topics in several engineering fields ranging from information theory to computer science. However, there is still a long way ahead in bringing to life all these theoretical concepts and developing efficient protocols that can exploit the inherent broadcast nature of wireless links to improve the performance of networks operating over the air interface. Among other open issues, the design of distributed cooperative Automatic Retransmission reQuest (ARQ) mechanisms remains as an interesting open area for research. The key idea behind distributed cooperative ARQ is that upon the reception of a packet with errors, a retransmission could be requested either from the original transmitting source station (traditional non-cooperative ARQ approach) or from any (or some) of the potential relay stations that overheard the original transmission. The concept of distributed cooperative

ARQ has been already tackled in the past from a fundamental point of view, considering simplified network topologies or ideal scheduling among the relays [4]-[6]. These previous works have put in evidence that distributed cooperative ARQ schemes may yield improved performance, lower energy consumption and interference generation, as well as extended coverage area by allowing communication between users with very low signal to noise ratios (SNRs). However, when different and independent relays are involved in a communication cooperative process, there comes up a multiple-user coordination problem. An inefficient algorithm to share the radio channel among the relays may spoil the benefits of the cooperative scheme. Therefore, the design and performance evaluation of efficient distributed Medium Access Control (MAC) protocols constitutes an interesting area for research if the benefits of distributed cooperative mechanisms are to be exploited.

Accordingly, a performance evaluation of the Persistent Relay Carrier Sensing Multiple Access (PRCSMA) protocol outlined in [7] (therein referred to as MRAC) is presented in this paper. The PRCSMA protocol is based on the standard IEEE 802.11 for Wireless Local Area Networks (WLANs) [8] and it was designed to coordinate the retransmissions from the relays in the distributed cooperative ARQ analyzed by Dianati et al. in [4]. The Standard-oriented design of PRCSMA has two main consequences; first, it could be easily implemented in already deployed commercial hardware by slightly modifying the firmware of common WLAN cards, and second, its performance may be tightly coupled with some network configuration parameters, such as the size of the contention windows, the number of active relays, the data transmission rates, or the offered data traffic. Therefore, the knowledge of the performance of this protocol under different network configurations constitutes an interesting topic that is tackled in this paper. Computer simulations have been carried out in order to evaluate the performance of the PRCSMA.

The remainder of this paper is organized as follows. An overview of the PRCSMA protocol is presented in Section II. Section III is devoted to the description of the system model considered for the performance evaluation. Simulation results and the discussion of the performance of the PRCSMA protocol are reported in Section IV. Finally, Section V concludes the paper and gives some final remarks as well as future lines of research.

1. PRCSMA Overview

The PRCSMA is a MAC protocol for wireless networks designed to coordinate the retransmissions of the relay stations in the distributed cooperative ARQ scheme described in [4]. In this scheme, upon the reception of a data packet containing errors, the destination station requests retransmissions from any of the relays which overheard the original transmission. Then, the destination station may be able to reconstruct the original packet with the different copies received from different relays. Therefore, any station which overhears a transmission from a source station becomes a potential helper to assist any station which receives a packet with errors.

The PRCSMA MAC protocol was designed with the constraint of modifying as less as possible the IEEE 802.11 MAC protocol [8]. Therefore, the basic rules of the contention among relays follow the ones specified in the Standard. The protocol works as follows: all the stations must listen to all the ongoing transmissions in order to cooperate in case it is required. They should keep a copy of any overheard data packet until either it is acknowledged by the next hop destination (not necessarily the final destination) or a certain timeout expires. Any destination station which receives a packet with errors initiates a cooperative phase by broadcasting a claim for cooperation (CFC) message, in the form of a control packet. Note that the error detection could be implemented by adding a Cyclic Redundancy Code at the header of all the data packets. The CFC is transmitted after a SIFS period. Regular data transmission in IEEE 802.11 is done after a longer silence period (DIFS), and thus, cooperation processes are prioritized over regular data traffic. All the stations which receive a CFC packet are invited to cooperate in the communication process. Those stations which fulfill some predefined relay selection criteria, which is not defined in the basic description of PRCSMA and which may also be attached to the CFC packet, become active relays and get ready to forward their information. This set of stations is referred to as the relay set. The specific PHY cooperative strategies applied by the relays as well as the reconstructing mechanism implemented at the destination station are out of the scope of the basic definition of PRCSMA, and thus, the retransmitted copy may be an amplified version of the original received packet at each relay, a recoded version of it, or any kind of space-time coded packet.

Within a cooperative phase, every potential relay will try to get access to the channel in order to relay the cooperative information as many times as possible (persistently). This cooperative information gets the form of a data packet, and it will be referred hereafter to as the cooperation packet. Therefore, during a cooperation phase, the network will be set into saturation conditions with a certain number of stations attempting to transmit data at the same time until the cooperation phase is finished. Accordingly, and in order to avoid a first collision with probability one upon cooperation request, all the relays should initiate a random backoff referral period before attempting to transmit for the first time. To do so, they independently initiate their respective backoff counters to a random value within the interval [0, CW], where CW is the initial contention window.

All the relays which already have a non-zero back-off counter upon the reception of the CFC packet use their current back-off counter value instead of resetting it to a new random value. It is worth mentioning that in saturation conditions, all the relays will have a non-zero Backoff counter unless they are actually transmitting.

The cooperation phase is finished whenever the destination station sends an ACK packet indicating the proper decoding of the original message. It should be emphasized that:

1. There is no ACK associated to each cooperation packet, in order to reduce the overhead in the cooperation phase.
2. The persistent behavior eliminates the possibility that a petitioner does not receive the required amount of cooperation packets, as opposed to what was presented in [9], by pretending there are infinite users trying to cooperate, as long as there is at least one potential relay. On the other hand, the relays could execute either the basic access or the collision avoidance (COLAV) access mode (RTS/CTS handshake) during a cooperation phase.

According to all this operation, there are many applications to which the PRCSMA protocol could be applied. For example, it may extend the coverage of centralized networks by allowing further stations to successfully communicate with the access point via intermediate relay stations. In addition, and depending on the specific relay selection criteria, the distributed cooperative ARQ mechanism of PRCSMA may increase the end to end communication rate between a given source and destination stations, thus, increasing the channel usage efficiency of the overall network. Therefore, the flexibility offered by the on-demand scheme using a CFC packet, which could specify any cooperation scheme or relay selection criteria, widens the application range of PRCSMA.

2. System Model

A custom-made C++ simulator has been implemented in order to evaluate the performance of the PRCSMA MAC protocol in a single-hop network (all the stations are in the transmission range of each other) formed by N stations. In addition, and in order to study the contention problem among relays and to avoid obscuring the performance evaluation with other system parameters, the following assumptions have been made:

- Original transmissions from a source station to any other destination station are always received with errors, and thus, a cooperation phase is always initiated after transmission of an original message. In this way, only the cooperative behavior is studied. These transmissions are performed at two constant common transmission rates, referred to as the *Main control_rate* and *Main data_rate*, indicating the bit rate for both the control and data plane transmissions, respectively.

- Relay retransmissions are assumed to be error-free. Although this assumption may seem too restrictive, the parameter considered in this paper for the performance evaluation will be the average number of required retransmissions, denoted by E[*r*], which will implicitly include the possible impairments of the wireless channel. These transmissions are performed at two constant common transmission rates, referred to as the *Relay control_rate* and *Relay data_rate*, indicating the bit rate for both the control and data plane transmissions, respectively.

The network configuration parameters are summarized in Table 1, and they have been set in concordance with the OFDM/DSSS PHY layer of the Standard IEEE 802.11g [10].

Table 1. Network Parameters

Parameter	**Value**	**Parameter**	**Value**
MAC header	34 bytes	SlotTime	10 μs
PHY header	96 μs	DATA packets	1500 bytes
ACK and CTS	14 bytes	SIFS	10 μs
RTS	20 bytes	DIFS	50 μs

Table 2. Sets of Transmission Rates (Mbps)

Name	**Main control_rate**	**Main data_rate**	**Relay control_rate**	**Relay data_rate**
1 – 54	1	1	6	54
6 – 54	6	6	6	54
24 – 54	6	24	6	54
54–– 54	6	54	6	54

3. Performance Evaluation

1.1 – Introduction

The PRCSMA performance evaluation presented in the following section has been done by varying the following parameters:

1. The number of active relays.
2. The transmission rates of both the main link (source-destination) and the relay transmissions (relays-destination), using the sets of rates specified in Table 2.
3. The average number of required retransmissions, denoted by E[*r*].
4. The access method of the relays: basic access or collision avoidance access with RTS/CTS exchange.
5. The size of the contention windows used by the relays.
6. The saturation condition of the network before initiating a cooperation phase.

It is important to emphasize that in order to evaluate the influence of the parameter under evaluation in each case, the rest of the parameters have been set to a constant vale.

1.2 – Performance Metric Definition

The performance metric considered herein is the distributed cooperative ARQ packet transmission delay. The packet transmission delay is defined as the total time required to successfully transmit a data packet from a source station to a given destination station, considering both the main original transmissions and all the retransmissions from the relay set.

We define:

- T_{tx} as the transmission time of a packet in the main link, from the source to the destination (accounting for both control and data transmissions),
- T_{CFC} as the cooperation request packet transmission time,
- $E[r]$ as the expected number of required retransmissions to properly decode a failed transmission,
- T_{r_tx} as the retransmission time, and
- $E[T_{cont}]$ as the average contention time to coordinate an average number of $E[r]$ retransmissions.

Therefore, the average packet transmission time when the distributed cooperative ARQ scheme is executed at layer-2 is denoted by $E[t_{COOP}]$ and it can be computed as

$$E[t_{COOP}] = T_{tx} + T_{CFC} + E[r]T_{r\_tx} + E[T_{cont}]. \tag{1}$$

1.3 – The Data and Control Transmission Rates

In order to evaluate the impact of the transmission rates on the performance of the PRCSMA, the CW has been set to 32, and the number of active relays (stations contending for the channel) in each cooperation phase has been set to 10. Relay stations use the basic access mode and the network is not saturated before initiating a cooperation phase.

The average packet transmission time is illustrated in (a) (b) Figure 1 as a function of the average number of required retransmissions and for different sets of transmission rates. As it could be expected, the ratio between the main transmission rates and the relay transmission rates determines how efficient the distributed ARQ mechanism is in comparison to the traditional non-cooperative ARQ approach wherein the retransmissions are only requested to the original source station and they can be performed without contention (retransmission can be transmitted one after another). At the limit where the relay stations transmit at the same rate that the source station, the total delay in the distributed scheme is higher due to the extra cost of coordinating the set of relays.

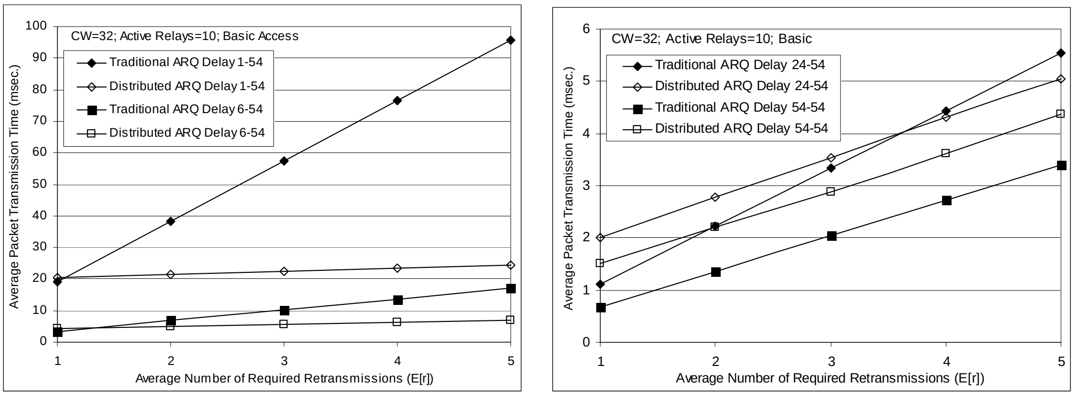
In the case of networks wherein the data transmission rate of each user is selected as a function of the channel state between source and destination stations, as in IEEE 802.11 WLANs, this behavior of PRCSMA shows that distributed cooperative ARQ schemes would be especially beneficial for those users located far away (for a given transmission rate) from the source station. Note that these stations will be prone to transmit at low transmission rates, and therefore, they could benefit from the faster retransmissions performed by relay stations half-way from the source.

1.4 – The Average Number of Required Retransmissions (E[r])

The same scenario as the one in subsection 1.3 is considered in this subsection. It can be inferred from (a) (b) Figure 1 that the cooperative distributed ARQ delay grows linearly with the average number of required retransmissions in PRCSMA.

Consider a network where the relays can transmit at very high transmission rates in comparison to the main transmission link. In this scenario, the cost of increasing in one the number of required retransmissions is very low in terms of delay. Therefore, it would be possible to employ simple cooperative schemes at the PHY layer that may require high number of retransmissions in order to properly decode an erroneous message.

However, if the relay transmission rates are comparable to that of the main link (source-destination), then the cost of a retransmission could spoil the benefits of the distributed cooperative ARQ scheme. In that case, the use of cooperative schemes that can reduce the expected number of required retransmission should be employed.



(a) (b)

Figure 1 Cooperation Delay as a function of the transmission rate ((a) relay low rate regime and (b) high rate regime)

1.5 – The Relays Access Method

In this case, all the relays use a contention window of 16 and the network is not saturated before initiating a cooperation phase. The selected transmission rate set is 24 – 54 Mbps (main– relays).

The cooperation delay as a function of the number of active relays and for different average number of required retransmissions is depicted in Figure 2 a. The depicted curves represent situations where the relays use either the basic access method or the collision avoidance access previous to the actual retransmission of the cooperative packets.

As it can be observed, and considering the absence of hidden or exposed terminals, the basic access is always the best configuration. Despite the use of a relatively small size of the contention window, the basic access method outperforms the collision avoidance in all cases. This is mainly due to the fact that the collisions in the control plane (at lower transmission rates) have a bigger cost in terms of delay than those in the data transmission plane. Therefore, it is possible to conclude that the COLAV mechanism adds too much overhead and compromises the benefits of the distributed cooperative ARQ scheme.

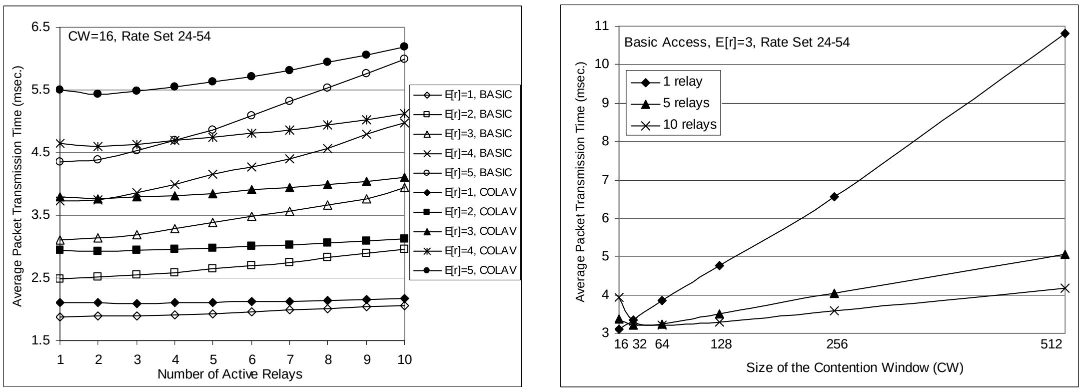
1.6 – The Size of the Contention Window (CW)

In this case the relay stations use the basic access mode and the network is not saturated whenever a cooperation phase is initiated. The average number of required retransmissions is 3 and three curves represent the delay with 1, 5 or 10 active relays in each case. The transmission rate set used in these simulations is 24 – 54 Mbps (main– relays).

(a) (b)

The cooperation delay as a function of the size of the CW is illustrated in Figure 2 b. For the single-relay case, the cooperation delay grows linearly with the size of the CW. Note that, in average, the wasted time due to the backoff will be equal to half the value of the CW, which corresponds to the expectation of the selected backoff counter.

The most interesting results can be extracted for low values of the CW. When the size of the CW is close to the number of active relays, the probability of collision gets higher, and thus, the cooperation delay is also increased. As an example, note that with 10 relays, if the size of the CW is set to 16, the delay is much higher than when only considering 5 active relays and with CW=16. Therefore, the size of the CW should be selected as a function of the number of active relays. Very high values of the CW will lead to too much time wasted in backoff periods, while too low values of the CW will lead to higher probabilities of collision. However, it is worth mentioning that in the case of not being able to operate at the optimum value of the CW, it would be more convenient to use higher values of the CW. Since relays use the basic access method, a collision has a greater impact on the cost than that of a number of idle slots during a backoff period.



(a) (b)

Figure 2 Cooperation delay with different access methods (a) and as a function of the size of the Contention Window (b)

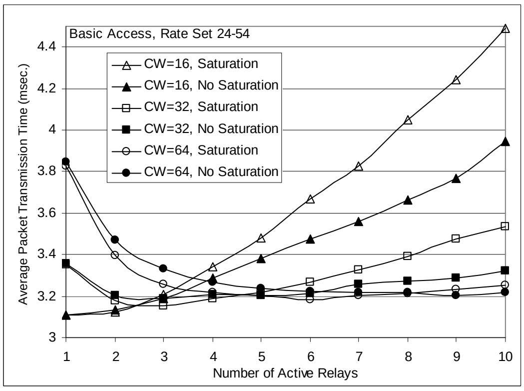


Figure 3 Saturated vs not-Saturated conditions before cooperation

1.7 – Saturated and non-Saturated Networks

The goal of this section is to compare the performance of PRCSMA in the cases where the network is either saturated or non-saturated before initiating a cooperation phase. Recall that if the network is saturated when a cooperation phase is initiated, all the relay stations use their current backoff counters for the cooperation phase. On the contrary, if the network is not saturated, all the relays stations set a new random value for the backoff counter. The average number of required retransmissions in this evaluation has been set to 3 and the transmission rate set used in these simulations has been set to 24 – 54 Mbps (main–relays). Different sizes of the contention window have been considered. The cooperation delay as function of the number of active relays and for different sizes of the contention window is illustrated in Figure 3. It can be seen that there are two operational regions; when the number of active relays is low, the saturated network behaves better in terms of cooperation delay than the not saturated network. However, when for higher number of active relays, it turns out to be that the non-saturated network performs much better and the cooperation delay is considerably lower than in the saturated case. This leads to the conclusion that in a saturated network it would preferable to reset the contention window of all those stations that become active relays in order to attain lower cooperation delays, that would, in the end, benefit the overall network performance.

4. Conclusions

A performance evaluation of the PRCSMA protocol for cooperative wireless networks where a distributed cooperative ARQ scheme is executed has been presented in this paper. The results show that the performance of the protocol may be strongly affected by the configuration of the network. Those scenarios where the main link between source and destination can only use low data rates are those where the benefits of the distributed cooperative ARQ scheme can attain best results. On the other hand, the size of the contention windows should be properly selected as a function of the number of activated relays for each cooperation phase in order to avoid either wasted time due to referral periods or existence of a high probability of collision. Simulations have also demonstrated that one of the design rules of PRCSMA should be changed; in order to attain better performance the backoff counter of the relays should be reset upon the start of any cooperation phase rather than using a previously set backoff value as specified in the basic definition of PRCSMA.

Ongoing and future work is aimed at analytically evaluating the performance of the PRCSMA protocol in order to assess its benefits from either network throughput, packet transmission delay or energy consumption points of view in the light of assessing its possible implementation in actual equipment.

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