PERFORMANCE EVALUATION OF A COOPERATIVE SCHEME FOR WIRELESS NETWORKS

J. Alonso-Zárate, J. Gómez, C. Verikoukis
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Castelldefels, Spain

L. Alonso
Dept. Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC)
Castelldefels, Spain

A. Pérez-Neira
Dept. Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain

ABSTRACT

It has been shown that the cooperation among nodes can improve the performance of a network under certain considerations. So far, research focus has been mainly put on cooperation and not on the coordination required to obtain this cooperation. In this paper we discuss how the MAC layer plays a key role in determining the effectiveness of a cooperative orthogonal multiple relay channel. We propose and analyze the performance of a novel MAC protocol based on the legacy IEEE802.11 standard in a representative and general study case scenario. The main conclusion of the study is that a proper selection of the MAC protocol being used in a cooperative system is highly relevant in order to actually achieve the benefits of this kind of systems.

I. INTRODUCTION

The inherent impairments of the wireless channel, such as the presence of fading or path loss due to the distance between any source and its intended destination, can considerably degrade the performance of a wireless network. In the recent years, it is remerging an old concept presented in [1] which puts in evidence that by means of cooperative transmissions, the network performance can be improved. Cooperative transmission is mainly motivated by the broadcast nature of the radio channel, which makes possible the reconstruction of a weak signal with multiple copies of it, obtained from independent transmission paths.

One possible cooperative diversity scenario is formed by a single transmitter and a group of potential receivers. Once a receiver is selected by the transmitter to be the destination of its information, the rest of the nodes remain as potential relays, which we denote by the relay set. The whole scenario forms the cooperative transmission set [2].

In most of the previous work on cooperative transmission, focus has been put on analyzing the gains of cooperation [1],[3], and on defining medium access control protocols (MAC) to manage the communication in the cooperative transmission set as in [2],[4] and [5]. However, how to coordinate transmissions among the relay set has not been considered in depth.

This paper continues a previous design of the relay network proposed in [6], whose main feature is its practicality at the PHY level. The scenario represents a situation that commonly takes place both in communication networks and in real life.

Imagine that we have four people having a meeting in a room, and let us call them A,B,C and D. Suddenly, someone enters into the room and claims a message for B. For whatever reason, B is not able to understand the contents of the message, so he asks A,C and D to repeat the message for him. In wireless networks, this real situation can be reproduced to improve the communication efficiency between pairs of source and destination nodes.

A feasible MAC protocol for such a network is proposed and analyzed. It is based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol employed in legacy IEEE 802.11 wireless networks. The new proposal is called Multiple Relay Access Control Protocol (MRAC).

We have only considered low Signal to Noise Ratio (SNR) values between source and destination, since these are the scenarios where cooperation is potentially beneficial. When high SNR is available, it is optimum to transmit at first hop, avoiding the cost of retransmitting.

There is a wide range of applications in growing interest that are characterized by low SNR values between transmitter and receiver, such as:

- Sensor networks, where node’s life time has to be maximized, and hence the available transmission power is very low.
- Noisy environments where communication might be affected with either high levels of noise or interference from other networks. The latter is going to be specially relevant in a near future, with the deployment of heterogeneous wireless networks.
- Energy-constrained ad hoc networks, where the target is to minimize the transmission power.
- High-bandwidth communication networks, since the noise power depends on the available bandwidth.

The rest of the paper is organized as follows. Section II presents the cooperative scenario under study. Section III is devoted to the problem statement, whereas in section IV the proposed scenario is analysed. In Section V the performance of the MAC protocol in the cooperative scenario is discussed. In the light of a practical evaluation, in Section VI we present the description of the novel proposal, MRAC. In Section VII, computer simulations are presented and the more relevant results are discussed. Finally, Section VIII concludes the paper and outlines the future lines of research.

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II. COOPERATIVE SCENARIO

We focus on the scenario presented and analysed in [6] and depicted in Figure 1. Let S be a source node sending data to a destination node D, which is at a distance $d$ from S. We consider a relay set composed of $N$ relay nodes surrounding node D. Therefore, the scenario is composed by a total number of $N+2$ nodes. Each relay node $r_i$, where $i = 1, 2, ..., N$, is situated at a distance $d_i$ from node D. We consider that $d >> d_i$ and, therefore, the SNR received at each of the nodes of the relay set and node D, when node S transmits a packet, is the same.

We define $P_e$ as the bit error rate (BER) from the source to the destination and the relay set, and $P_s$ as the BER in the transmission from the relay set to the destination. We assume that $d >> d_i$ and that $P_s >> P_e$.

![Figure 1 Cooperative scenario under consideration](image)

III. PROBLEM STATEMENT

The cooperation works as follows. First, node S sends a data packet to node D, which is also received by all nodes forming the relay set. In the case that node D is not able to decode the packet due to its erroneous detection, it asks for its neighbourhood to retransmit a copy of the same packet in order to attempt to reconstruct it. Those nodes that received the original packet will try to send it to node D, regardless of whether their received packet has errors or not. It has to be noted that node D can reconstruct the original packet with the received copies from the relay set by means of either a Maximum Ratio Combining (MRC) receiver, or by applying majority voting in a bit by bit fashion, as reported in [6].

IV. SCENARIO ANALYSIS

Let us first define $M$ as the modulation size employed at the physical layer (PHY) and the amount of bits per symbol as $b = \log_2(M)$. The increase of the number of retransmissions might be interpreted as an increase of the SNR received at destination D, and hence a reduction of the BER for a fixed transmission rate. However, it does also imply a lost of bandwidth efficiency.

In a wide range of real applications, the goal is to get a certain Quality of Service (QoS), which can be mapped into a target BER. Therefore, in order to analyse the influence of cooperation but maintaining a constant BER in the transmission, the modulation size $M$ must be increased as the value of $K$ grows. We denote by $b(K)$ the bit rate as a function of the number of total transmissions (including retransmissions). The final transmission rate between nodes S and D for a given symbol time $T_s$ when $K$ total transmissions are performed is expressed by

$$R_s[K] = \frac{b[K]}{K} \frac{1}{T_s} [bps] \quad (1)$$

where the effects of MAC have been neglected.

One of the benefits of underlying PHY architecture presented in Figure 1 is that it is possible to find an easy relationship between the BER, the modulation size and the number of relays, which is not usually easy to obtain in relay networks.

Particularizing (1) for a M-QAM modulation, and considering that node D combines the cooperative retransmissions with a Maximum Ratio Combing (MRC) receiver, the end-to-end (E2E) effective transmission rate $R$ can be approximated by [7],

$$R_s[K] = \frac{1}{K T_s} \log_2 \left(1 + \frac{3}{2} \left[ \gamma \sqrt{\frac{K \pi}{2 P_e}} \right] \frac{1}{SNR_{S\to D}} \right) [bps] \quad (2)$$

where $P_e$ is the target BER, $SNR_{S\to D}$ is the SNR at the main link between the nodes S and D, and $\gamma$ is a constant.

Figure 2 shows the value of $R$ as a function of the number of retransmissions $K-1$ for different SNRs and being $P_e = 10^{-3}$. It is worth mentioning that direct communication between source and destination nodes is not possible for any of the considered SNRs. For example, in the case of $SNR=10$dB, communication is only possible by means of at least 2 retransmissions, while in the case of $SNR=0$dB, communication is only possible with a minimum of 7 retransmissions.

It is also interesting to appreciate the peaky aspect of the curves in Figure 2. A retransmission can derive into two completely different consequences. Observe for example the curve for $SNR=10$dB. When two retransmissions are required, the achievable throughput is close to 0.7Mbps. If the number of retransmissions is increased by one, the total transmission rate decays to 0.5Mbps due to the time required to perform this new retransmission. However, if another retransmission is carried out, the total transmission rate grows up to 0.6Mbps. This is due to the fact that this new retransmission derives into an increase of the SNR such that makes
possible to increase the transmission rate. Therefore, although the addition of a new retransmission implies a high cost in terms of bandwidth allocation, in some cases it allows to increase the effective transmission rate by increasing the modulation index $M$.

As a result of this behaviour, the design target is to fix the operating points at those number of retransmissions that attain the highest E2E transmission rate. For instance, in the case of having an SNR=10dB, the system should ensure a number of retransmissions equal to 2 (or at least the local maximums at 4, 7 or 11 retransmissions), avoiding other situations that lead to a less efficient behaviour of the cooperative system. This could be achieved by means of a previous dialogue between source and destination nodes in order to set the proper modulation index $M$.

Anyway, neither equation (1) nor (2) take into consideration the time required to coordinate the $K$-I retransmissions and the loss of effective rate due to it. This latency can not be neglected as the number of $K$-I retransmissions increases. In a real system, the use of a MAC protocol at the link level is imperative in order to coordinate the transmissions of the relay set. The efficiency of such a protocol is of considerable relevance, since an inefficient coordination could lead to the lost of the cooperative benefits. In Section V we further analyze the impact of the MAC protocol in the proposed cooperative scenario.

V. MAC Impact Discussion

We define $T_p$ as the time required to transmit a packet, and its expression is given by,

$$T_p = L T_b + L \frac{T_c}{b[K]} [s]$$  \hspace{1cm} (3)$$

Where $T_b$ is the bit time, and $L$ is the total length in bits of the data packets. However, when $K$ transmissions are required, this term may be scaled at least by a factor $K$. Furthermore, a contention time among the retransmissions has to be added to this expression. Therefore, when considering the MAC, the total time to transmit one data packet is given by $T_p^{MAC}$ and can be expressed as

$$T_p^{MAC} = (K T_p + T_c)[s]$$  \hspace{1cm} (4)$$

Where $T_c$ is the contention time imposed by the MAC protocol in order to coordinate the $K$-I retransmissions. It is important to note that this MAC delay depends on the total number of required transmissions to coordinate, on the number of total possible relays that compete for the channel, and obviously on the selected MAC protocol.

Therefore, we can define the final effective transmission rate between S and D, for a total number of $K$ transmissions and for a fixed number of $N$ possible relays as $R_{MAC}[K,N]$, being

$$R_{MAC}[K,N] = \frac{L}{KT_p + T_c} [bps]$$  \hspace{1cm} (5)$$

By using (3) in equation (5) and considering (1), the total transmission rate achieved in the proposed cooperative set when $K$-I retransmissions are required is given by

$$R_{MAC}[K,N] = R_e[K] \left( \frac{1}{1 + \frac{T_c}{L} R_e[K]} \right) [bps]$$  \hspace{1cm} (6)$$

As expressed in (6), when the MAC protocol is considered, the total E2E throughput when $K$-I retransmissions are required is equal to the theoretical value $R_e[K]$, without considering the MAC contention time, multiplied by a factor that depends on the MAC protocol, the number of retransmissions, and the ideal transmission rate.

In this paper we design and evaluate the performance of a novel MAC protocol based on the CSMA/CA MAC protocol, employed in IEEE802.11 wireless terminals, and tailored for the specific requirements of our scenario. The new proposal is called MRAC (Multiple Relay Access Control Protocol).

We use this performance as a reference value, and we try to determine the corresponding value of $T_c$ for different values of $K$. Next section is devoted to the description of the new protocol.

VI. MRAC Protocol

Although in most of the communication protocols the transmission session is started by the node having data to transmit, in the presented scenario the one triggering the communication protocol is the receiver node when asking for cooperation.

The focus of this paper is not on designing an optimal evolution of CSMA/CA to suit this kind of scenarios, but however, some adaptations have to be done to the standard in order to be applied to our cooperative scenario. For a complete description of the CSMA/CA MAC protocol, the reader is referred to [8].

A new control frame is defined at the MAC layer in order to Claim For Cooperation (CFC). This CFC could be implemented following the structure of the Request to Send (RTS) packet considered in CSMA/CA, but indicating in both source and destination fields the address of the node asking for cooperation.

When node D needs to ask for cooperation, it must listen to the channel for a DCF Inter Frame Space (DIFS) time,
similar to the method used for transmitting an RTS packet. If the channel remains idle for that time, it will be able to broadcast the CFC. Otherwise, it will contend for the channel following the regular rules determined by CSMA/CA.

Once the cooperation requesting node is able to decode the original packet, it broadcasts an ACK packet. The mission of this ACK is twofold: i) It informs its neighbourhood that the cooperation process is finished, and ii) it informs the original source node that the packet has been properly decoded. Note that at the reception of the CFC, the source node waits until the arrival of the ACK from the intended destination.

From an implementation point of view, the virtual carrier sensing implemented in the 802.11 MAC protocol should be disabled during the regular operation of the protocol (without cooperation). All nodes must be aware of the current state of the communications, and keep a copy of all data packets transmitted through the channel in order to be able to cooperate in case of request. However, it might be activated during the cooperation phase.

The operation of the proposed mechanism is depicted in Figure 3, where the two-relay \((K-1=2)\) case is represented and the contention phase has been intentionally omitted.

**VII. SIMULATION AND RESULTS**

In order to analyse the performance of the cooperative scenario, and using the MRAC, we have developed a C++ simulator. The parameters of the MAC protocol have been set to the values indicated in Table 1, and according to the values in [8].

Following the scenario and notation used in Section II, we have set \(N=10\). We assume that all transmitted packets from S to D require cooperation, and we have iterated the value \(K-1\) from 1 to 10. It is important to note that the number of potential relays is fixed to 10 regardless of the number of required cooperation. We assume also that the 10 relaying nodes are within the transmission range of the destination node, although not necessarily all relay nodes might communicate with each other. The target BER has been set to \(10^{-3}\).

Figure 4 depicts the total effective transmission rate achieved between the source and destination as a function of the total number of required retransmissions, for three different values for the SNR between the original source and the destination nodes. Both analytical (ideal) and simulated results are presented. Although the curves show a similar behaviour, there is an important difference in the simulations because they do consider the time needed for coordination among the transmission of the different relay nodes through the operation of the MAC protocol. Note that the higher the SNR, the more relevant this difference. Since we consider that the BER between the relay set and destination is negligible, control packets are sent at the same rate selected for the data packets. However, when the rate is doubled, the MAC delay is not divided by two. This is due to the fact that the MAC protocol includes silence intervals (SIFS and DIFS) that are totally independent of the transmission rate used in the network, and as a consequence, it provides a net performance gain.

Therefore, there is a transmission rate lost due to the extra overhead added by the MAC protocol. The percentage of this rate lost is represented in Figure 5 and defined as,

\[
\eta_{\text{MAC}} = \left( \frac{R_s[K] - R_{\text{MAC}}[K,N]}{R_s[K]} \right) \times 100 \tag{7}
\]

Note that expression (7) is valid for any general MAC.

Two conclusions can be extracted from Figure 5. First, the higher the SNR in the main link, the higher the effective transmission rate can be, but the higher relative impact of the MAC protocol. On the contrary, the lower the SNR, the lower the effective transmission rate can be, but the actual MAC impact in relative terms is also lower. This is due to the fact that the time required to coordinate \(K-1\) retransmissions when using MRAC is approximately the same, independently on the transmission rate. However, when the transmission rate is low, the percentage of time devoted to the MAC protocol is relatively low, since the transmission of packets lasts a considerable amount of time. The second conclusion arises from the fact that the three curves decay as the number of retransmissions grow. Indeed, when \(K\) is greater, the overhead added by the MAC protocol becomes proportionally less relevant.

Figure 6 shows the value for the contention time performed by MRAC as a function of the number of retransmissions and for different values of the SNR in the main link. It could seem reasonable that as the number of retransmissions grows, the contention time of the MAC protocol is also increased. Nevertheless, as aforementioned, the cooperative system makes possible to increase the effective transmission rate as the number of retransmissions grows. Therefore, when the modulation size is increased, the MAC delay decreases due to the higher transmission rates being used.

From combining the information of Figure 4 and Figure 6, we can see that the delay grows linearly with the number of retransmissions while the transmission rate is maintained, and abrupt changes are caused when the number of retransmissions forces an increase of the modulation size. Once again, lower SNR forces to transmit at lower transmission rates, and
hence, the delay is higher for the case of 0dB than for the case of 10dB, for example.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFS</td>
<td>10 µs</td>
<td>CWmin</td>
<td>31</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 µs</td>
<td>CWmax</td>
<td>1023</td>
</tr>
<tr>
<td>ACK</td>
<td>14 bytes</td>
<td>L</td>
<td>2312 bytes</td>
</tr>
<tr>
<td>RTS</td>
<td>20 bytes</td>
<td>Bandwidth</td>
<td>1 MHz</td>
</tr>
<tr>
<td>CTS</td>
<td>14 bytes</td>
<td>BER</td>
<td>10^{-3}</td>
</tr>
</tbody>
</table>

Table 1 MRAC Parameters

![Figure 4 Total transmission rate as a function of the number of retransmissions for different SNR values](image)

![Figure 5 Percentage of lost in the transmission rate when considering MAC](image)

![Figure 6 MAC Contention time of MRAC](image)

Another relevant conclusion of these results is that the bit rate adaptation achievable with the proposed cooperation generates an approximately constant average MAC delay, regardless of the value of $K-1$ required retransmissions. For example, when SNR=10dB the MAC delay is equal to 11ms when either three or eight retransmissions are performed. This is crucial in some actual situations, for example, when due to either a extremely low available SNR or a strict power consumption constraints, the required amount of retransmissions is high.

VIII. CONCLUSIONS

In this paper we have discussed and analysed the impact of the MAC layer in a cooperative system. By means of multiple retransmissions of the same packet, cooperative diversity can help to increase the performance of a wireless network. However, it has to be taken into account that as the number of retransmissions increases, the delay added due to the need for coordination of these retransmissions must be taken into account.

We have analysed a specific and representative cooperative scenario and we have presented the performance of a novel MAC protocol (MRAC) by means of computer simulations. Both analytical and simulation results demonstrate that the MAC protocol has an important role in the performance of a relay network. Therefore, the design of an efficient MAC protocol tailored for the specific requirements of cooperative systems is a wide research topic in the near future.

In this sense, our future work is going to be focused on designing an optimum MAC protocol for a cooperative scenario and evaluate the potential obtainable gains in comparison to the currently available alternatives. Moreover, interesting topics not covered by now might be the proper selection of the amount of required retransmissions or the selection of the most adequate nodes in the relay set to execute the cooperation.

IX. REFERENCES


