NCMOB-MAC: A Network Coding-based MAC protocol with mobility support

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***Abstract*—In this paper, a novel Network Coding (NC)-aided Medium Access Control (MAC) protocol with mobility support (NCMOB-MAC) is presented. The proposed protocol is compatible with Automatic Repeat reQuest (ARQ) techniques and can be applied in Vehicular Ad hoc Networks (VANETs). NCMOB-MAC proposes a new way of coordinating the communication between a sender, a moving destination and a set of fixed relay nodes. The relays employ different Contention Window (CW) sizes to assign priorities and optimize the NC opportunities. Extensive simulations have been carried out to evaluate the performance of the protocol and the results show an improvement in throughput and energy efficiency compared to conventional NC-aided MAC protocols.**

***Index Terms*—Cooperation, MAC, Mobility, Network coding, VANET**

I. INTRODUCTION

Mobile Ad hoc Networks (MANETs) and Vehicular Ad hoc Networks (VANETs) have been designed taking into account the motion of the wireless nodes in a mobile environment. MANETs is the general term for any kind of self-organized mobile networks, where mobile nodes can operate without a network infrastructure. VANETs is a specific term, derived from MANETs, that refers to wireless ad hoc networks whose nodes are vehicles like cars or buses. One of the main characteristics of ad hoc networks is the lack of a fixed infrastructure, and one of the concepts that can be exploited in this kind of networks is the cooperation among the nodes [1].

Network Coding (NC) [2] is another concept that has been studied together with cooperation, in order to improve the network performance. The main idea behind NC is that intermediate nodes in a mesh network combine the received packets before forwarding them to the next hop. In this way, the overall throughput and efficiency of the network is improved by decreasing the number of necessary transmissions. Various research studies have been carried out in this field, mainly in the physical [3] [4] and the Medium Access Control (MAC) layer [5] [6].

Several works focus on developing new MAC protocols that take into account cooperation and NC in order to deal with different issues [5]–[8]. However, the impact of mobility is considered only in [7] and [8], although none of these protocols is explicitly designed for mobile scenarios.

Focusing on VANETs, CAH-MAC [9] is a cooperative MAC protocol that improves the network throughput by utilizing the unreserved time slots in the contention phase to retransmit packets which have failed to be received. NCCARQ protocol [10] is another MAC protocol that joints NC, cooperation and Automatic Repeat reQuest (ARQ) techniques to coordinate the transmissions of several nodes in a VANET scenario. However, NCCARQ studies the performance of the protocol in static scenarios, without taking into account the mobility of the nodes.

Most of the aforementioned works are backwards compatible with the Distributed Coordination Function (DCF) of the IEEE 802.11 standard, where the first node that senses the medium free wins the contention phase and starts transmitting a packet after a random backoff time. In a mobile scenario, this random selection is not efficient, as the moving destination may be eventually out of the range of the selected relay. Therefore, assigning different priorities is a challenge. GeoMAC [11] is a MAC protocol for VANETs that exploits spatial diversity by allowing the adjacent nodes to the source to opportunistically forward data packets. The main point in GeoMAC is that the stations use a geographically-oriented backoff mechanism, depending on the geographic distance to the destination, to select the forwarder that is most likely to succeed in the transmission. Other ways of selecting priorities can be implemented by modifying the Contention Window (CW) size of the relay nodes. In [12], the CW size is adapted according to the instantaneous collision rate to enable service differentiation in a VANET scenario. In [13], the authors propose a sliding CW, so different CW ranges can be selected depending on the priority of the traffic flows. However, none of these studies apply NC techniques.

In this paper, we introduce a novel NC-aided cooperative ARQ MAC protocol with mobility support (NCMOB-MAC), based on the NCCARQ [10] protocol, that coordinates the communications between several nodes in a VANET scenario and deals with the problem of increased packet loss due to mobility. The contributions of this paper are the following:

- The proposed protocol combines NC, node cooperation and CW adaptation for a better relay selection strategy in order to assist the bidirectional communication between two nodes in a mobile scenario.

- We increase the throughput and the energy efficiency, while we reduce the packet loss, comparing to a baseline scenario where NCCARQ is applied.

The rest of the paper is organized as follows. Section II presents the general system model. Section III describes the NCCARQ protocol and the challenges that arise in mobile scenarios. Section IV introduces NCMOB-MAC, while Section V presents the simulation results for our scenario. Finally, Section VI concludes the paper.

II. System Model

In this section, we present the scenario and the parameters that are involved in our case, which are shown in Fig. 1. In this figure, two nodes want to communicate, a fixed node A and a moving node B, and n relay (R) nodes are placed between them to help in the bidirectional communication when there is an error in the packet reception. In particular, when an error occurs, the node B broadcasts a control packet, named Request For Cooperation (RFC), to the relay nodes together with a data packet b that is destined to node A. The relays will buffer the overheard packet a from the node A and the received packet b, to perform NC techniques before forwarding the coded packet to the nodes A and B. Once these nodes receive the coded packets, they will send the respective acknowledgement (ACK) packets.

The node B is moving at a constant speed ($\mathbf{v}$) towards the edge of node A's range. The distance ($\mathbf{d}$) between the relays is fixed. Two ranges are defined for this scenario: i) the **RFC range** and ii) the **Data range**. The **RFC range** is defined by the distance that achieves the RFC packet, which is a control packet sent with a low modulation rate, thus being received by more relay nodes. However, data packets are sent with a higher modulation rate, and thus they achieve lower distance, defined as **Data range**. It is worth noting that the *active relay set* (i.e., the group of nodes that will be able to cooperate and perform NC techniques) will be formed by the relays inside the intersection of the Data ranges.

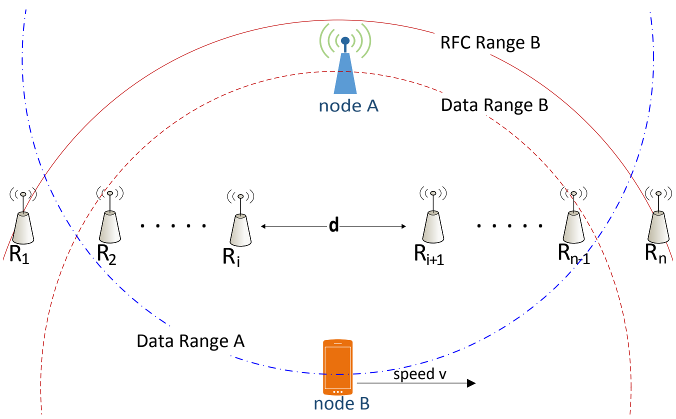

Fig. 1. System model.

III. NCCARQ-MAC Overview and Challenges

A. NCCARQ overview

NCCARQ-MAC [10] is an NC-based cooperative ARQ MAC protocol that coordinates the transmissions of several nodes in an ad hoc network, similar to the scenario shown in Fig. 1 but with all static nodes. The operation of NCCARQ-MAC is based on: (i) the ability of stations to request cooperation from the nearby relay nodes when they receive an erroneous data packet, and (ii) the capability of the relay nodes to perform NC techniques to the overheard and received packets before transmitting them. In NCCARQ, the actual relay that will cooperate in the communication with the nodes is completely random, since all relays select a backoff value from [0,31], as the IEEE 802.11 MAC protocol defines, to enter the contention phase before transmitting a data packet.

B. Challenges

It is worth noting that NCCARQ protocol operates properly in static scenarios. However, in a mobile scenario, e.g., when the node B is moving, NCCARQ may suffer from packet loss due to the mobility. There are two reasons for this issue:

1) As the node B is moving, it may be out of the range of the relay node that won the contention phase, as the actual cooperating relay selection is completely random.
2) In NCCARQ, the *active relay set*, formed upon the reception of the RFC packet, is greater than the actual group of relay nodes that have received both data packets from nodes A and B and, thus, are able to perform NC techniques.

The challenge is to adapt this protocol to a mobile scenario, modifying the access rules giving priorities to the relay nodes that are closer to the node B, in order to reduce the loss of packets and ACKs and guarantee that the selected relay will be able to perform NC.

IV. NCMOB-MAC Protocol

A. Description

NCMOB-MAC is introduced to coordinate the transmissions between two stations (A and B), and several relay nodes, in cooperative mobile scenarios, where the direct transmissions fail.

The main objective is to improve the throughput of the system, reducing the number of lost packets due to the mobility of the node B. In order to achieve this goal and similar to NCCARQ, the relay nodes must perform a promiscuous listening of the network in order to buffer the packets that the nodes A and B are transmitting and to be able to cooperate if an RFC packet is received. These packets will be stored in the buffers of the relays until the ACKs are received and another transmission round is initiated.

Unlike NCCARQ, in order to give priority to the relay nodes that are closer to the node B, NCMOB-MAC changes the CW size, according to the position of the node B with respect to the relay nodes. All relay nodes will act independently, so they do not know in advance the position, the information or the transmission state of the other nodes. This lack of communication between relay nodes will help reducing the traffic (overhead) in the network as they do not have to exchange control packets. In order to estimate the relative position of the node B with respect to the relay nodes, Received Signal Strength Indicator (RSSI) based techniques can be used, since RSSI is inversely proportional to the distance between the nodes. Accordingly, an RSSI threshold for all relay nodes will be set and they can decide the appropriate CW size based on the RSSI from the node B.

The communication starts when the node A sends a packet a to the node B, which is not received correctly, e.g., the node B cannot retrieve the data. This packet a is overheard by the relay nodes and stored in their buffers. Then, node B sends an RFC control packet, asking the nearby relay nodes for cooperation. This control packet has higher priority over regular data traffic, as it is sent after the node senses the medium free for a Short Inter Frame Space (SIFS), whereas data traffic is sent after the medium is detected idle for a DCF Inter Frame Space (DIFS) period of time. If the node B also has a data packet to send to the node A, e.g., packet b, it will send both the RFC packet followed by the data packet to the relay nodes. Unlike NCCARQ, the *active relay set* will be formed by the group of relay nodes that receive both RFC and data packets, not only the RFC packet. The reason is that not all the relays that receive the RFC control packet can cooperate in the communication and perform NC, as explained in Section II. In this way, assigning priorities to the closer relay nodes, with respect to the node B, the protocol ensures lower packet loss due to the mobility. These priorities will be set changing the CW size. The relays will auto-assign themselves a CW size value depending on the RSSI value from the node B. If the RSSI is higher than the threshold, the protocol sets a smaller CW size value (compared to the default CW size of 32) to the relay nodes, thus giving these nodes higher priority to transmit (CW_{high_p}). If the RSSI is lower than the threshold, the relay nodes will auto-assign a larger CW size that will give lower priority (CW_{low_p}).

All relay nodes inside the *active relay set* now have stored the overheard packet a and the received packet b in their buffers. These relay nodes perform the XOR operation $a \oplus b$, and enter the contention phase, selecting their own random backoff value, in order to access the medium and broadcast the XORed packet. At this point, three different cases can occur:

1) Just one relay node gains access to the medium and the coded packet is transmitted correctly to the nodes A and B.
2) There is a collision between relay nodes that transmit the XOR packet at the same time, i.e., their backoff counters reach zero at the same time.
3) Just one relay node wins the contention phase but the coded packet is lost. The reason is that the relay node is either no longer inside of the Data range or has not yet entered in the Data range of node B.

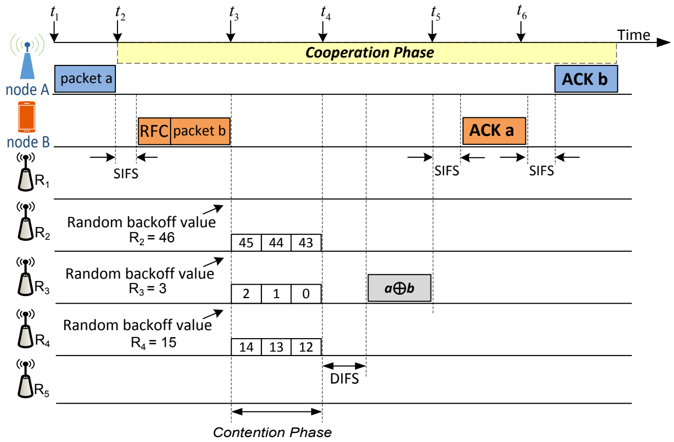

Fig. 2. Illustration example for the packet exchange.

Once both nodes A and B receive the XORed packet, they will acknowledge the received data packets. In the protocol operation we assume that ACKs are received by the destination and sender nodes. Furthermore, after collisions or lost packets, the CW is not doubled, but relays perform another random backoff selection with the same previous CW size value and enter the contention phase again with the rest of the relays.

B. Operational example

For a better understanding of the protocol operation we provide an example, considering a scenario with five (5) relay nodes. Fig. 2 illustrates the described procedure.

1) At the time t_1, the node A sends a packet a to a moving node B.
2) At instant t_2, an error occurs and the node B is not able to retrieve the content of packet a, so it broadcasts an RFC message to the nearby relay nodes together with the data packet b.
3) In this example all relays will receive the RFC packet, however, just R_2, R_3 and R_4 will receive both the RFC and the data packet b, and form the *active relay set*. At instant t_3, these relays will auto-set their CW size values according to the RSSI value received from the node B. In this particular case, R_3 is the closest node to the node B, so it will set its CW size to CW_{high_p}=8 for example. We suppose that R_2 and R_4 are farther compared to R_3, so their CW size will be CW_{low_p}=64. This way the probability that R_3 wins the contention phase is higher than if we had all relays with the same CW size. Once the CW size is selected, each relay will select a random value and start the backoff procedure.
4) At instant t_4, the backoff counter of R_3 reached zero, so it broadcasts the XOR packet $a \oplus b$.
5) Once the node A receives the coded packet, at time t_5, it can decode packet b and send the corresponding acknowledgement.
6) The node B will ACK packet a, at instant t_6, once it retrieves the data from packet a.

V. Performance Evaluation

A. Simulation scenario

The purpose of this section is the performance assessment of the proposed MAC protocol. For this reason we have developed a C++ simulator that executes the rules of our protocol. The results of NCMOB-MAC will be compared with the NCCARQ-MAC protocol under the same simulation parameters and conditions.

In NCCARQ, the relay nodes will not be assigned any priorities, since they all select the default CW=32. If a collision occurs between two or more relays, the involved nodes double their CW size and select another random value for their backoff counter. In case the packet is lost because of the mobility of the node B (the same case as before) another random value will be selected from the default CW size without doubling it.

The simulated scenario is similar to the one in Fig. 1, which consists of a node A, a moving node B and a set of relay nodes. As the node B is moving, it will eventually get out of node A's range, so in order to make a realistic approach for the simulations, we assumed that this scenario is repeated consecutively, so after node B moves out of the first node A's range, it will enter the range of another static node A that wants to start a communication.

In Table I, all the parameters of the simulated scenario are presented. Five different scenarios of the NCMOB-MAC protocol have been considered, changing the CW size that gives higher priority (CW_{high_p}) to the relay nodes that receive a higher RSSI value, with CW values 2, 4, 8, 16 and 32. Meanwhile, the other relay nodes that are inside the *active relay set*, and receive lower RSSI than the threshold, will be set with a CW_{low_p}=64. The simulations will evaluate the system depending on the distance (**d**) between relays, in the range 10 to 60 m. The number of relay nodes is set to 200, but a random number of relays can be set without interfering with the general response of the system. The radius of the RFC range is set to be double (100 m) compared to the radius of the Data range (50 m). There are 4 different types of power consumed by the nodes, i.e., P_{TX} and P_{RX} when the nodes are transmitting or receiving packets, P_{idle} when the nodes are listening to the medium without communication and P_{sleep} is the power consumed by the relays that do not receive neither control nor data packets.

For the simulations we have made the following assumptions:

1) The packet sent from node A is always received with an error by node B, as this node is always moving towards the edge of node A's range. In this way, cooperation will always be needed.
2) Node B always has a data packet to send to node A, so the relays can always create a coded packet.
3) There are no errors in the transmissions coming from the relays.

The metrics used to evaluate the performance of both protocols are: throughput, number of collisions, packet loss ratio and energy efficiency. The energy performance of the protocols will be calculated following [14], where the energy efficiency metric η is defined as:

TABLE I
Simulation Parameters.

Parameter	Value	Parameter	Value
CW_{high_p}	[2 , 32]	Data rate data packets	54 Mb/s
CW_{low_p}	64	Data rate control packets	6 Mb/s
d distance	[10 , 60] m	time slot	10 μs
RFC range	100 m	SIFS	10 μs
Data range	50 m	DIFS	50 μs
v speed	20 m/s	MAC header size	34 bytes
n	200	PHY header size	96 bytes
P_{TX}	1900 mW	RFC size	14 bytes
P_{RX}	1340 mW	ACK size	14 bytes
P_{idle}	1340 mW	Data Packet size	1500 bytes
P_{sleep}	132 mW		

$$\eta = \frac{\text{total amount of useful data delivered (bits)}}{\text{total energy consumed (Joule)}} \qquad (1)$$

B. Simulation results

Fig. 3 shows a comparison of the throughput performance of the NCMOB-MAC protocol, varying the CW_{high_p} value, and the NCCARQ protocol, with regard to the distance between relays. It is noticeable that all the CW sizes of NCMOB-MAC achieve better throughput than normal NCCARQ, independently of the CW_{high_p} value. The improvement of the throughput of NCMOB-MAC with respect to NCCARQ varies from 30% to 45% depending on the selected CW_{high_p} value. Even with a CW_{high_p} value of 32, the same as NCCARQ, NCMOB-MAC achieves better throughput because the relays that are farther than the node B select a CW size of 64, so NCMOB-MAC still gives higher priority than NCCARQ. The curve with CW_{high_p}=2 gives the worst throughput at the shortest distances between relays, but gives the best throughput values when there are longer distances between relays. In a static scenario, setting a low CW size for the relays would probably worsen the system throughput due to an increase in the number of collisions. However, in a scenario that includes mobility, the increase in the number of collisions, due to the small CW_{high_p} value, is widely compensated by a reduction in the number of lost packets, as it is shown in Fig. 4.

Fig. 4 compares the number of collisions and lost packets versus the distance between relays. As expected, as farther away the relay nodes are between them, less nodes will be inside the *active relay set* so less nodes will have the same priority, i.e., CW size, which will decrease the number of collisions. The number of lost packets does not vary substantially until the the distance between the nodes is great enough to lead to a loss of packets. As expected, the lower the CW size in NCMOB-MAC is set for the relay nodes, the lower the loss of packets is due to the mobility.

In Fig. 5, we can see the energy efficiency of both protocols with regard to the distance between relays. This graph is directly related with the throughput graph, as the curves with better throughput will also provide higher energy efficiency.

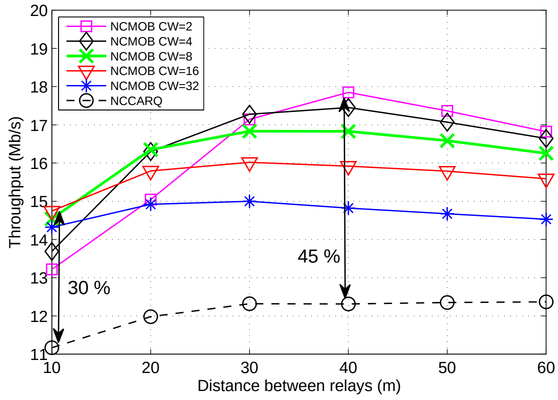

Fig. 3. System's throughput comparison.

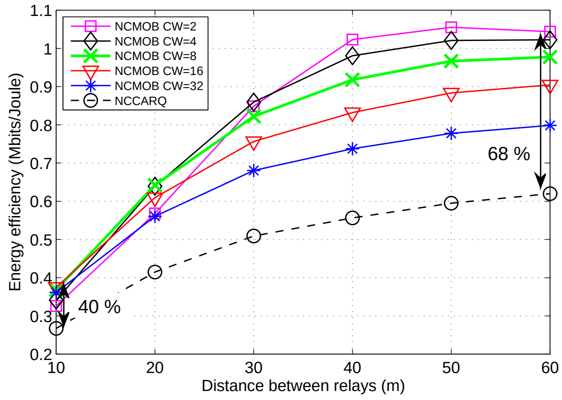

Fig. 5. System's energy efficiency.

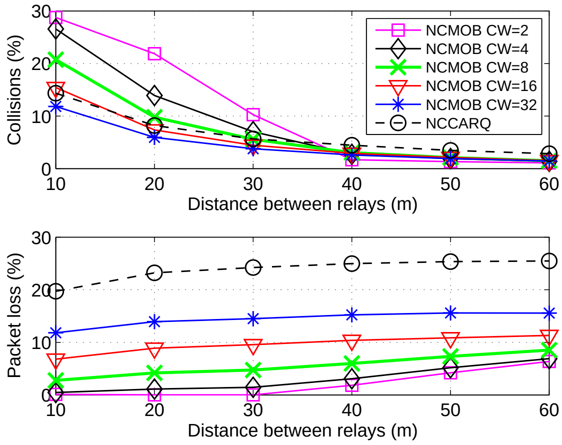

Fig. 4. Percentages of collisions and lost packets.

In this case the improvement in terms of energy efficiency, compared to NCCARQ, ranges from 40% to 68% depending on the CW size of NCMOB-MAC and the distance between relays.

VI. Conclusions

This paper presents a novel Network Coding-based MAC protocol with mobility support (NCMOB-MAC) for VANETs. Using NC, cooperation between relays and CW adaption, the developed protocol assigns different priorities to the relay nodes, changing the CW size, depending on the position of a moving node in order to reduce the packet loss. Simulations demonstrate that the proposed solution improves the network throughput up to 45% and the energy efficiency up to 68%, compared to a baseline NC-based cooperative MAC protocol.

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