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Network coding-based cooperative ARQ scheme for VANETs

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ABSTRACT

In this paper we introduce a novel Network Coding-based Medium Access Control (MAC) protocol for Vehicular Ad Hoc Networks (VANETs) that use cooperative Automatic Repeat reQuest (ARQ) techniques. Our protocol coordinates the channel access among a set of relays capable of using network coding in order to minimize the number of the total transmissions, thus enhancing the performance of the network in terms of Quality of Service (QoS) metrics. The proposed solution is compared to other cooperative schemes, while analytical and simulation results are provided to evaluate our protocol.

1. Introduction

Vehicular Ad Hoc Networks (VANETs) have been deployed to facilitate the communication between vehicles. Recently, IEEE 802.11p (2010) has been introduced in order to deal with the special characteristics of VANETs, i.e. the high mobility of the nodes and the rapid changes in the topology. This new standard, also known as Wireless Access in Vehicular Environment (WAVE), is based on Carrier Sensing Multiple Access (CSMA), while it adopts service differentiation using adaptive backoff window sizes to achieve better QoS performance (Enhanced Distributed Channel Access—EDCA). In addition to the standardization, it would be interesting to investigate how the recent innovative techniques, such as cooperation among nodes and network coding, could affect the inter-vehicle communication. These new technologies create the need of designing new MAC protocols that exploit their benefits to efficiently use and manage the network resources.

The concept of cooperation was introduced by Cover and Gamal (1979) in their fundamental paper on relay channels. Their work analyzed the capacity of the three-node network consisting of a transmitter, a receiver and a partner (relay).[1] In their model, the spatial diversity gain is obtained by exploiting different channels seen by different nodes for transmitting data. On the other hand, network coding is an area that emerged in 2000 (Ahlswede et al., 2000), and since then has attracted an increasing interest, as it promises to have a significant impact in both theory and practice of networks. We can broadly define network coding as allowing intermediate nodes in a network to not only forward but also process the incoming information flows. Most of the work on this topic focuses on the physical layer aspect while only few works examine these techniques considering the MAC layer effect (Katti et al., 2008; Argyriou, 2009; Zhang et al., 2008). Furthermore, the main assumption in the majority of the works is that only one relay contributes to the communication, thus ignoring the impact that the collisions and the idle slots cause to the network's performance.

In this context, we propose a new MAC protocol (NCCARQ-MAC) that coordinates the transmissions among a set of relay nodes which act as helpers in a bidirectional communication that takes place in a vehicular environment. The main contribution of our proposed scheme lies on combining both cooperative and network coding techniques in order to enhance the system's performance. To the best of our knowledge, there is no proposed MAC protocol in the literature that implements network coding in cooperative ARQ schemes with more than one relay, while there is a limited number of papers that apply network coding in cooperative schemes that take advantage of the multi-rate capability of wireless standards (Tan et al., 2007).

The rest of the paper is organized as follows. Section 2 gives the basic background on cooperative networking and outlines the related work on MAC layer protocols for both simple and network coding-based cooperative schemes in the literature, especially in the field of VANETs. In Section 3 we introduce our proposed NCCARQ-MAC protocol along with a detailed mathematical analysis. The validation of the analytical model and the numerical results are provided in Section 4. Finally, Section 5 concludes the paper.

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[1] Note that the words "partner", "relay" and "helper" are used interchangeably in this paper.

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2. Background and related work

2.1. Cooperative communication

In the context of cooperative communications, several schemes focused on MAC layer have been already proposed in the literature (Lu et al., 2007; Alonso-Zarate et al., 2008; Liu et al., 2005; Guo and Carrasco, 2009; Zhu and Kuo, 2007). These works can be classified into two main categories: (i) the cooperative ARQ-based protocols and (ii) the protocols that transform one-hop transmissions to multi-hop transmissions by exploiting the multi-rate capabilities of the wireless systems.

2.1.1. Cooperative ARQ-based protocols

Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) algorithms are two basic error control methods for data communications (Lin and Costello, 1983). ARQ schemes have received considerable attention for data transmissions due to their simplicity and higher reliability, compared to FEC schemes.

Regarding the protocols falling in this category (Lu et al., 2007; Alonso-Zarate et al., 2008), the retransmissions are initiated by the destination after an erroneous packet reception. The helpers in a network are enabled to relay the original packets to a specific destination, as ARQ defines, using higher data rates or better channel conditions in terms of Signal-to-Noise Ratio (SNR) values.

In the context of Vehicular Networks, Kaul et al. (2008) have proposed a new protocol, GeoMAC, that exploits spatial diversity by allowing the nodes adjacent to the source to opportunistically forward data packets. In GeoMAC, the stations use a geographically-oriented backoff mechanism which uses the geographic distance to the destination as a heuristic to select the forwarder most likely to succeed. VC-MAC (Zhang et al., 2009) is another cooperative ARQ protocol, designed mainly for broadcasting scenarios in VANETs. Specifically, as the nodes move fast, it is possible that after a certain period of time they will be outside the range of a specific gateway that broadcasts data packets. However, other vehicles – moving relatively at the same speed – remain in their proximity, thus being potential relays.

2.1.2. Protocols that transform one-hop transmissions to multi-hop transmissions

Using the concept of adaptive modulation (Morinaga et al., 1997), mobile stations in a multi-rate wireless network assign the modulation scheme and the transmission rate according to the detected Signal-to-Noise Ratio (SNR) and the required transmission quality. Each modulation scheme could be further mapped to a range of SNR in a given transmission power. To achieve high transmission efficiency in wireless systems, stations select the highest available rate modulation scheme according to the detected SNR.

The protocols of this class (Liu et al., 2005; Guo and Carrasco, 2009; Zhu and Kuo, 2007) transform single one-hop transmissions to multi-hop transmissions according to the channel conditions. Specifically, when the channel state between the relay and the destination is better than the channel between the source and the destination, a two-hop transmission is preferred instead of the direct transmission.

ADC-MAC (Zhou et al., 2011) is a novel protocol that coordinates the scheduled transmissions with regard to the channel conditions among the source, the destination and the relay nodes in a vehicular environment. In ADC-MAC, a three-party handshake takes place between the nodes in order to be decided which is the most efficient way for the data to be transmitted.

2.2. Cooperation and network coding

Last years, there is a trend towards using network coding in cooperative communications. The initial attempts for developing network coding-based cooperative communications focused on physical layer schemes(Wang and Giannakis, 2008; Xiao et al., 2007). These approaches refer to the coding gain and optimal power allocation in simple cooperative topologies, usually considering one relay or cooperation among the users.

However, the innovation of using network coding in cooperative communications is not confined only in the physical layer. Tan et al. (2007) presented one of the few works that focus on MAC layer aspect of network coding-based cooperative communication. Their proposed protocol, called CODE, exploits the benefits of both network coding and multi-rate capability of IEEE 802.11 Standard. Specifically, the coding of the packets takes place at the relay nodes, under two basic conditions: (i) the direct link between the sender and the receiver is poor and exists one or more relay candidates that experience better link conditions and (ii) the traffic is bidirectional.

In VANETs' domain, a content distribution protocol has been introduced by Lee et al. (2006). Their proposed scheme, named CodeTorrent, adopts Random Linear Network Coding (RLNC) techniques to enhance the network performance. However, the implementation of RLNC in VANETs has been later proven to be affected by the resource constraints of the mobile nodes (Lee et al., 2008).

3. Proposed network coding-based cooperative ARQ MAC protocol

3.1. Protocol description

NCCARQ-MAC has been designed to coordinate the transmissions among a set of relays that support a bidirectional communication between two nodes in a vehicular environment. The first goal of NCCARQ-MAC is to enable the mobile stations to request cooperation by the neighboring nodes upon an erroneous reception of a data packet. The second design goal of our proposed protocol is to allow the helper nodes to perform network coding techniques to the packets to be transmitted before relaying them.

The first requirement of NCCARQ-MAC is that all nodes in the network should operate in promiscuous mode in order to be able to listen to all ongoing transmissions and cooperate if required. However, this is not an energy issue in VANETs, since the wireless interfaces running on the vehicle's battery power. The second basic requirement of NCCARQ-MAC is that the nodes should store a copy of any received data packet (regardless of its destination address) until it is acknowledged by the destination station.

In NCCARQ-MAC, a cooperation phase is initiated once a packet is received erroneously by the destination. Some factors that adversely affect the correct packet reception are the long distance between the nodes, the slow fading (shadowing) inside dense populated areas, etc. Several error detection mechanisms such as Cyclic Redundancy Code (CRC) can be applied in order to perform error control to the received messages. Therefore, the destination station initiates the cooperation phase by broadcasting a Request for Cooperation (RFC) message after sensing the channel idle for SIFS (Short Inter Frame Space) period of time. This message has the form of a control packet and higher priority over regular data traffic, since data transmissions in 802.11 take place after a longer period of silence (DCF Inter Frame Space—DIFS). Furthermore, in the special but not rare case of bidirectional traffic, i.e. when the destination station has a data packet for the source station, the packet is broadcasted piggybacked on the RFC message.

The stations that receive the RFC packet are potential candidates to become active relays for the communication process. Therefore, the relay set is formed upon the reception of the RFC and the participants stations get ready to forward their information. Since the partners have already stored the packets that