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Energy efficient network coding-based MAC for cooperative ARQ wireless networks

Angelos Antonopoulos [a,*], Christos Verikoukis [a], Charalabos Skianis [b], Ozgur B. Akan [c]

[a] Telecommunications Technological Centre of Catalonia (CTTC), Castelldefels, Barcelona, Spain
[b] Department of Information and Communication Systems Engineering, University of the Aegean, Karlovassi, Greece
[c] Department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey

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ABSTRACT

In this paper we introduce a network coding-aided energy efficient Medium Access Control (MAC) protocol that coordinates the transmissions among a set of relay nodes which act as helpers in cooperative Automatic Repeat reQuest-based (ARQ-based) wireless networks. Applying network coding techniques, we achieve to increase the energy efficiency of the network without compromising the system performance in terms of Quality of Service. Our proposed solution is evaluated by both analytical and simulation results.

1. Introduction

Energy efficiency has always been a critical design parameter for wireless networks. Recently, the trend towards designing energy-aware communication protocols has become more intense due to the scarcity of the energy resources. The purpose of these new protocols is twofold: (i) to extend the battery's life in portable devices and (ii) to efficiently use the environment's natural resources. Therefore, "green"[1] communications have become one of the hottest topics in the research community.

Cooperation among nodes and network coding are two techniques that have been introduced to improve the network performance and provide the communication with diversity, robustness, security and high data rates. The benefits of these technologies can be exploited by designing new MAC protocols that efficiently use and manage the network resources.

The concept of cooperation was introduced by Cover and Gamal [1] 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[2]. 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 emerged in 2000 [2,3], and since then has attracted an increasing interest, as it promises to have a significant impact in both theory and practice of networks. Network coding can be broadly defined as and advanced routing or encoding mechanism in the network layer, which allows intermediate nodes in a network not only to forward but also to process the incoming information flows. Most of the work on this topic focuses on the physical layer aspect [4–7] while only few works examine these techniques considering the MAC layer effect [8–10]. Furthermore, the main assump-

* Corresponding author. Tel.: +34 93 645 29 00.
E-mail addresses: aantonopoulos@cttc.es (A. Antonopoulos), cveri@cttc.es (C. Verikoukis), cskianis@aegean.gr (C. Skianis), akan@ku.edu.tr (O.B. Akan).

[1] "Green" refers to all environment-aware methods.

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

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tion in the majority of the works is that only one relay contributes to the communication, thus ignoring the impact of collisions and idle slots to the network performance.

In this context, we propose a novel network coding-based cooperative ARQ MAC (NCCARQ-MAC) protocol, backwards compatible to the legacy IEEE 802.11 [11], that coordinates the transmissions among a set of relay nodes which act as helpers in a bidirectional communication. Our main contribution lies on the following:

1. Network coding techniques are used along with cooperative ARQ to enhance the system performance.
2. Less control packets – and consequently less overhead – are added in the network.
3. The contention phases are decreased, hence reducing the idle and the collision times.
4. An analytical model for the energy efficiency of the system is presented.

The rest of the paper is organized as follows. Section 2 provides the reader with 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. 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.

2. Background and related work

2.1. Cooperative communication

In the context of cooperative communications, several schemes focused on the MAC layer have been already proposed in the literature [12–18]. 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 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 [19]. 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 [12–14], the retransmissions are initiated by the destination after an erroneous packet reception. The helpers in a network are enabled to relay the original packets, as ARQ defines, using higher data rates or better channel conditions in terms of Signal-to-Noise-Ratio (SNR) values.

2.1.2. From one-hop to multi-hop transmission via adaptive modulation

By using the concept of adaptive modulation [20], mobile stations in multi-rate wireless networks assign the modulation scheme and 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 [15–18] transform single one-hop transmissions to multi-hop transmissions according to the channel conditions. Specifically, the routing of the packets takes place by taking into account the channel state between the source, the relay and the destination, and therefore a multi-hop transmission may be preferred instead of the direct one.

2.2. Cooperation and network coding

Lately, there is a trend towards incorporating network coding in cooperative communications. The initial attempts for developing network coding-based cooperative communications were focused on physical layer schemes [21–23]. 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 applying network coding in cooperative communications is not confined only in the physical layer. Umehara et al. [24] developed analytical models for the throughput and the delay in slotted ALOHA with network coding (S-ALOHA/NC) for single-relay multi-user wireless networks with bidirectional data flows. Recently, Munari et al. [25] introduced PHOENIX, which exploits the advanced Multiple-Input-Multiple-Output (MIMO) network coding principle to enable the relay nodes to code their own data packets along with noisy versions of packets received from other nodes. Another work that deals with the MAC layer of network coding-based cooperative communication was presented by Tan et al. [26]. Their proposed protocol, called CODE, exploits the benefits of both network coding and multi-rate capabilities 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.

2.3. Network coding and energy efficiency

The impact of network coding in "green" communications has already started to be studied, especially in broadcast and multicast scenarios [27–30]. The recent research work that investigates the energy aspect of network coding applications, deals mostly with the network layer. Cui et al. [31] introduced CORP by using a suboptimal scheduling algorithm that exploits network coding opportunities, thus achieving a significant power saving over pure routing. More recently, Miao et al. [32] proposed an energy efficient broadcast algorithm using network coding for gradient-based routing (GBR) in wireless networks. Their proposed algorithm aims to reduce the network traffic and, consequently, the energy consumption, thus prolonging the network lifetime.