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A cooperative MAC protocol with rapid relay selection for wireless ad hoc networks

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ABSTRACT

We propose a cooperative MAC protocol with rapid relay selection (RRS-CMAC) to improve the cooperation efficiency and multiple access performance in wireless ad hoc networks. In this protocol, if the data rate between a sender and its recipient is low, an optimal relay is selected by a rate differentiation phase (RDP), priority differentiation phase (PDP), and contention resolution phase (CRP) for relays with the same priority. In the RDP, each contending relay determines its data rate level based on the data rate from the sender to itself and that from itself to the recipient, and then broadcasts busy tones to its neighbor nodes or senses the channel according to the values of its binary digits, which are determined by its data rate level. Relays with the highest data rate levels win and continue to the next phase. In PDP, these winning relays send busy tones or sense the channel according to their own priority values, with the highest priority relays winning in this phase. Then CRP is performed using k-round contention resolution (k-CR) to select a unique optimal relay. Relays sending busy tones earliest and for the longest duration proceed to the next round, while others, sensing a busy tone, subsequently withdraw from contention. A packet piggyback mechanism is adopted to allow data packet transmission without reservation if the winning relay has a packet to send, and the direct transmission rate to its recipient is high. This reduces reservation overhead and improves channel utilization. Both theoretical analysis and simulation results show that the throughput of the proposed protocol is better than those of the CoopMACA and 2rcMAC protocols.

1. Introduction

Wireless ad hoc networks offer the benefits of ubiquitous connectivity and mobile access [1]. However, fading, shadowing, and path loss problems severely affect the data rate and reliability of packet transmissions. Cooperative communication techniques offer a solution to these challenges [2,3]. In using these, mobile nodes share their own transceivers to form a virtual multiple-input multiple-output system to achieve spatial diversity gain in their packet transmissions [4], thereby effectively combating signal fading, and improving data transmission rates and communication reliability [5,6].

Early research on cooperative communication techniques mainly focused on the physical (PHY) layer. It is generally assumed that channel state information (CSI) is used to select relays [7,8]. A recipient can receive signals from the sender and multiple relays, either simultaneously using multiple orthogonal channels or a space-time coding scheme, or sequentially using different time slots to improve the channel capacity, bandwidth efficiency, and power efficiency, and decrease the bit error rate (BER) [9].

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Recently, more and more research has focused on applying a cooperative communication technique to the upper layers. However, cooperative transmission is also subject to challenges at the different upper layers, and some protocol modifications are required to achieve the objectives of cooperation. In fact, proper protocol designs at the upper layers can guarantee the achieved cooperation gain in the PHY and upper layers [10,11].

Recent approaches exploited the network-level cooperation in wireless environment [12–17]. A key difference between PHY layer cooperation and network layer cooperation is that the latter can capture the bursty nature of traffic and consider relaying at a protocol level [12–14]. In [15], only one relay is introduced and allowed to forward a correctly decoded packet from the sender. Accordingly, both stability region and throughput region in terms of packet/slot are characterized through queueing-theoretic techniques. Two-relay network-level cooperation is considered in [12]. Furthermore, Pappas et al. [13] introduce the notion of partial network-level cooperation by adding a flow controller to the relay node for the traffic coming to the relay from the source, thereby ensuring the stability of the queues. The impact of energy constraints on a network with a source, a relay and a destination under random access of the medium is studied in [14]. The source and the relay nodes have external arrivals and network-level cooperation is employed in which the relay forwards a fraction of the source's traffic to the destination. Based on these, Kashef and Ephremides [16] investigate the interaction between energy harvesting, cooperative relaying, and stability in wireless networks, characterize the stability region of the optimal partial relaying strategy for the source and the relay in a simple relaying network with a single relay that generates its own traffic, and obtain the optimal value of the relaying parameter to maximize the source stable throughput for a given relay throughput. The authors in [17] adopt an advanced physical (PHY) layer cooperation and an "intelligent" cognitive network-layer cooperation in order to improve the stable throughput region of the system. A dynamic decode-and-forward (DDF) policy is incorporated to allow relaying assistance during the source transmission and provide more cooperative opportunities. In addition to this PHY-layer relaying, the cognitive cooperation is supported by an adaptive/non-adaptive superposition scheme which allows the relay node to simultaneously forward packets from different users. In this paper, we focus cooperative transmission on medium access control (MAC) layer.

In wireless ad hoc networks, the MAC protocol is always used to address the channel-sharing problem for multiple nodes, which is critical to efficiently reserve and reuse channel resource, and then improve network performance [18,19]. A good MAC protocol with multihop fair access can satisfy the upper bounds on network utilization and lower bounds on delay for multihop wireless networks [20]. Furthermore, the design of a better MAC protocol employing node cooperation can further improve network performance and exploit the cooperation gain based on spatial diversity achieved by the PHY layer. However, it is difficult for multiple nodes to share channel information owing to the time-varying and distributed features of multihop wireless ad hoc networks, with the result that node cooperation strategies either cannot be implemented or do not achieve improved cooperation [10]. Therefore, a relay selection scheme is critical to the design of cooperative MAC protocols. A general method for designing a cooperative MAC protocol is to embed a novel relay selection scheme into an already-proposed or improved MAC protocol.

The objective of our work is to design a novel distributed cooperative MAC protocol to achieve maximum cooperation efficiency by promptly selecting an optimal relay based on the instantaneous channel quality, i.e., instantaneous signal-to-noise ratio (SNR) between a communication node pair. Here, the SNR is influenced by several factors such as distance, frequency, propagation environment, and total noise at the receiver. To improve cooperation efficiency further by reducing extra reservation overhead, the optimal relay can piggyback its own data packet with different recipients compared with the sender after relaying the sender's data packet. Most importantly, the proposed cooperative MAC protocol is compatible with the legacy IEEE 802.11 protocol, so that it can be deployed in coexistence scenarios with wireless local area networks.

Motivated by the above idea, we propose a cooperative MAC protocol with rapid relay selection (RRS-CMAC) for wireless ad hoc networks to solve the problem of effective relay selection to achieve greater cooperation efficiency. If the direct data rate between a sender and its recipient is low, the relay selection phase is initiated. In the first contention phase, relays with the highest data rates from the sender to themselves and from themselves to the recipient are selected through sensing or transmitting busy tones according to the virtual rate identification (ID) corresponding to their data rates. In the second contention phase, relays with their own data packets to send and for which the recipients are available, continue the k-round contention resolution (k-CR) process proposed in [21] to select an optimal relay with the highest data rate from itself to its own recipient for packet piggyback transmissions, thereby reducing contention overhead and improving cooperation efficiency. Moreover, if the winning relays in the first contention phase have no data packets to send or if none of their recipients is available, they continue the k-CR process to select only one relay to forward the sender's data packet to the recipient. If the direct transmission rate from the optimal relay to its own recipient is high, the packet piggyback mechanism is adopted to allow this relay to transmit its own data packet without channel reservation after transmitting the data packet for the sender, which can further improve the protocol performance.

The contributions of this paper are as follows:

- We propose a cooperative MAC protocol that integrates relay selection, packet piggyback, and medium access for the application of cooperative communication techniques to the MAC layer.
- We design a relay selection scheme including a rate differentiation phase (RDP), priority differentiation phase (PDP), and contention resolution phase (CRP) to select a unique optimal relay promptly from all potential relays with high probability thereby further exploiting cooperation gain. Any existing collision resolution schemes can be used in the CRP.