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An Energy-Aware Cross-Layer Cooperative MAC Protocol for Wireless Ad Hoc Networks

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ABSTRACT

Cooperative communication (CC) has recently emerged as an effective technique to combat the channel impairment, energy limitation and radio spectrum constraints. Physical-layer Network Coding (PNC) is an alternative applied in wireless networks to reduce transmission time slots and deliver higher throughput while also being energy-efficient. In order to benefits from both CC and PNC characteristics an efficient Medium Access Control (MAC) protocol is required. This study introduces a new cooperative MAC protocol called EAP-CMAC (Energy Aware Physical-layer Network Coding Cooperative MAC) that integrates cooperative communication into PNC in wireless ad-hoc networks. In EAP-CMAC, the best transmission mode is selected among direct transmission, traditional cooperation and PNC-based transmission by considering the destination queue and source-destination link quality. Moreover, a joint relay selection and power allocation algorithm is proposed based on location information and the nodes residual energy that significantly improves the network lifetime and energy saving in wireless networks. The simulation results indicate that EAP-CMAC outperforms IEEE 802.11 and CoopMAC in terms of network lifetime by 50% and 140% respectively. Furthermore, the proposed optimal power allocation enhances EAP-CMAC performance in terms of network lifetime by 7% compared to equal power allocation.

1. Introduction

Green communication and networking has recently gained much attention, as it not only guarantees Quality of Service (QoS) and minimizes cost and energy consumption, but it is also environmentally benign. Therefore, the paradigm shift toward energy-efficient communication has intensified in various technical approaches, such as resource management, power control, cross-layer optimization, and energy-aware protocol design (Li et al., 2011; Daquan et al., 2013). Cooperative communication has been newly introduced as an effective, energy-efficient transmission technique, in which the terminal nodes are encouraged to share resources in order to help each other in a cooperation mode, resulting in higher diversity gain and throughput achievement. In short, cooperative communication networks have emerged to combat channel impairment, energy constraints and restricted radio spectrum resources (Weihua and Ismail, 2012; Zhengguo et al., 2011). In cooperative communication, mobile terminal nodes share information, construct a virtual antenna and exploit spatial diversity, whereas MIMO technology imposes higher restrictions in the implementation of handling nodes and small devices.

The vast majority of previous studies on cooperative communication have concentrated on various issues and challenges in the physical layer as well as information-theoretic approaches (Sendonaris et al., 2003; Hunter and Nosratinia, 2006; Jie et al., 2006; Bletsas et al., 2006). Nonetheless, coordination between the physical layer and higher layers (e.g. MAC layer) is essential, especially in time-varying channels where greater difficulty arises in link construction. In addition most previous works on cooperative communication have considered simplified scenarios including three-party nodes (source/relay/destination) and assumed the presence of idle Medium Access Control (MAC), which accurately coordinates data transmission among users. However, the benefits of cooperative communication may be corrupted by traditional higher layer protocols designed for legacy non-cooperative systems. Thus, an appropriate coordination and scheduling between nodes in the MAC layer is essential to improve end-to-end performance and makes cooperation more feasible and practical. Generally, cooperative MAC protocols are divided into

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contention-based and contention-free (reservation-based) schemes. In contention-free protocols, each time slot is allocated to an individual node, thus the nodes do not contend each other to access the channel. However, this strategy generally suffers from dynamic network topology changes and transmission delay in dense networks. Contention-based protocols do not require complex coordination, thus being more robust against topology changes, and face lower overhead and energy consumption in sparse networks. However, these benefits may decline with increasing traffic load due to corresponding increment in collision that causes lots of energy wastage for retransmission and idle listening. In addition, bounded latency cannot be guaranteed in contention-based networks. Therefore, an appropriate scheduling and MAC protocol not only prevents numerous retransmissions due to collision, but also reduces end-to-end communication latency.

Since 2000, network coding was developed into an encoding mechanism or advanced routing, in which intermediate nodes can forward combinations of incoming packets by mixing rather than forwarding them individually (Ahlswede et al., 2000; Li et al., 2003). Network coding has been extensively applied and evaluated in various communication networks, including cognitive, wireless sensor, ad hoc networks (Lee et al., 2014; Mohammed Hassan et al., 2013; Mu et al., 2011). Physical-layer Network Coding (PNC), a sub-field of NC, was first proposed in Zhang et al. (2006) as a solution to exploit network coding and deal with superimposed electromagnetic (EM) signals in the physical layer. PNC-based protocols attain higher spectral efficiency, whereby two end-nodes simultaneously transmit their information in a medium access channel and share the broadcast channel through the network coding concept. Integration between the PNC and cooperative transmission is a green communications alternative when there are many active nodes in the network and traffic load is heavily congested in the application layer. Accordingly, coordination between potential relay nodes and two end nodes is vital in the MAC layer to develop more practical cooperation fast and reliably. The two main challenges in designing a PNC-based MAC protocol considered are as follows. First, an elaborate scheme should be designed to support simultaneous and collision-free packet transmission by two end nodes in the channel. Secondly, the designed protocol should be compatible with traditional cooperative protocols to avoid redundant PNC-based transmission if either direct or conventional cooperative transmission is more effective.

The majority of previous cooperative MAC protocols have mostly focused on throughput improvement and delay reduction, but at the cost of higher energy consumption and network lifetime degradation. Nonetheless, a few works have addressed energy efficiency and energy saving in cooperative networks. In Antonopoulos et al. (2013a), the authors proposed an energy efficient network coding-based cooperative MAC protocol, called NCCARQ-MAC, which coordinates the helper nodes in cooperative Automatic Repeat reQuest-based (ARQ) wireless networks. In another work (Wang and Li, 2013a), the authors proposed a network coding-aware cooperative MAC protocol called NCAC-MAC to increase throughput and reduce delay. However, in Antonopoulos et al. (2013a), the authors did not mention how the relay nodes set up their back off counter. In Wang and Li (2013a), the best relay is one that maximizes the aggregated throughput and minimizes the transmission delay. In this paper, energy-aware networks and PNC characteristics are exploited to elaborate a novel cross-layer Energy-Aware PNC-based Cooperative MAC protocol, namely EAP-CMAC. In addition, a joint relay selection and power allocation scheme is designed, which improves the network lifetime. The proposed relay selection considers energy consumption and the best relay is selected based on residual energy and the mobile nodes' position. EAP-CMAC, a compatible protocol, selects the most suitable relay node and transmission strategy among direct, cooperative and PNC-based transmissions according to the destination queue and source-destination link quality.

Mobile users in a Mobile Ad-hoc NETwork (MANET)can be connected through wireless links and communicate with each other through a direct link in an ad-hoc manners. A critical issue for continuous connection in MANETs is the mobile lifetime due to battery and energy resources scarcity. The proposed protocol provides the Quality of Service (QoS) required by the system, saves energy and increases network lifetime in MANET using a location-based relay selection and power allocation algorithm. In addition, the PNC scheme can be applied for video conferencing where two or several users multicast their data. Note, each relay node computes its own utility based on the information receive from RTS and CTS transmission. Afterwards, a backoff timer that is inversely proportional to the obtained utility is allocated to each relay node. The main contributions of this paper are as follows:

- A novel and adaptive cross-layer cooperative MAC protocol called EAP-CMAC is proposed to exploit the PNC in cooperative networks, intended to save energy and improve network lifetime and throughput.
- A new relay selection algorithm is suggested to find the best relay based on the terminal nodes' residual energy. Accordingly, a detailed power allocation is designed to provide the required QoS.
- A 3D Markov model is planned to analyse the protocol and consider the probability of successful transmission in the network.
- An accurate Network Allocation Vector (NAV) setting is provided for spatial reuse enhancement. The simulation and analytical analysis illustrate that EAP-CMAC significantly improves network lifetime compared to CoopMAC and legacy IEEE 802.11.

The remainder of this paper is organized as follows: Section 2 presents the related works. In Section 3, the basic information and models are presented. Section 4 provides details of the proposed EAP-CMAC. Section 5 presents the detailed relay selection and power allocation algorithm proposed based on residual energy and the utility function. In order to facilitate spatial reuse in the network and increase its efficiency, a NAV setting is designed in Section 6. Section 7 describes the analytical model of the proposed EAP-CMAC. The simulation and numerical results are presented in Section 8 and the conclusions are summarized in Section 9.

2. Related Works

In general, contention-based cooperative MAC protocols are divided into proactive and reactive schemes. In a reactive scheme, the nodes enter cooperation mode whenever direct transmission fails and a Negative ACK (NACK) is received (Antonopoulos et al., 2013a; Adam et al., 2013; Antonopoulos et al., 2013b). Although reactive protocols prevent signalling overhead, they incur great energy costs since all relay nodes are forced to listen to direct transmission. In the proactive scheme, the proper relay(s) is/are selected before data transmission; however, this causes system overhead increase. In the proactive scheme cooperation is facilitated by either a table-based approach or a contention-based algorithm.

There are numerous cooperative MAC protocols whose aim is to exploit the multi-rate-capability of PHY in IEEE802.11 to respond to different channel conditions and maximize network throughput. As initial work in Pei et al. (2007), the authors proposed a proactive cooperative MAC protocol called CoopMAC, which utilizes high-rate nodes to speed up data transmission rather than the direct link with low quality and low rate. In another work (Hao and Guohong, 2006), the authors proposed a relay-enabled Distributed Coordination