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A cross-layer multi-hop cooperative network architecture for wireless ad hoc networks ☆,☆☆

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ABSTRACT

In this paper, a novel decentralized cross-layer multi-hop cooperative network architecture is proposed and presented. This cross-layer architecture introduces a new cooperative flooding scheme and two decentralized opportunistic cooperative forwarding mechanisms based on randomized coding, and a Routing Enabled Cooperative Medium Access Control (RECOMAC) protocol that enables cooperative forwarding, while incorporating physical, medium access control (MAC) and routing layers. RECOMAC employs randomized coding to realize cooperative diversity, so that relay selection and actuation mechanisms are alleviated and the MAC costs are reduced. The coded packets are routed in the network via the proposed cooperative forwarding schemes, which opportunistically form cooperative sets within a region, not needing a prior route to be established. Essentially, in the RECOMAC architecture, the routing layer functionality is submerged into the MAC layer to provide seamless cooperative communication, while the messaging overhead to set up routes, select and actuate relays is reduced. We evaluate the performance of RECOMAC in terms of network throughput, delay and MAC and routing overhead, in comparison to the conventional architecture based on the well-known IEEE 802.11 MAC and Ad hoc On Demand Distance Vector (AODV) routing protocols. RECOMAC is shown to provide quite significant improvement by an order of magnitude difference in all investigated performance metrics, under a variety of scenarios, considering different network sizes, static and mobile scenarios and networks with multiple flows.

1. Introduction

Wireless ad hoc networking paradigm has emerged as a powerful platform for applications such as wireless mesh networks, wireless sensor networks and mobile networks, owing to their attributes such as minimal configuration requirements, quick deployment and decentralized operation. Different from centralized wireless networks, where nodes communicate with a base station or an access point over single hop links, in wireless ad hoc networks the end-to-end communication is carried over multiple hops realized through intermediate nodes.

Despite many potential applications as exemplified above, the performance of wireless ad hoc networks is still limited because: (i) The end-to-end path consists of multiple concatenated unicast links along specified nodes on a predetermined path. Those unicast links suffer from errors due to channel impairments caused by fading and mobility, and failure of even a single link can make the entire end-to-end path inoperable, requiring route rediscovery and maintenance procedures. In case of harsh environmental

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conditions, the route discovery phase may need to be repeated several times causing heavy messaging burden, thereby leading to wasted network bandwidth and degraded throughput. (ii) Routing messages are delivered by contending for the available medium. In addition to the burden for rediscovery, the contention avoidance and resolution mechanisms also steal from the network bandwidth that could otherwise be used for data communication. Moreover, as the network size is increased, the message overhead of routing strategies is also increased, resulting in further degradation in throughput and delay performance.

Cooperative diversity has emerged as an efficient method to realize diversity gains offered by multiple input single output (MISO) systems without the need for employing multiple antennas on wireless nodes [1]. Cooperative diversity exploits the wireless broadcast advantage. Nodes which overhear a transmission emulate an antenna array, for example employing space–time codes [2], and they provide the receiver with multiple copies of the original signal through independent channels, thereby forming a virtual MISO (v-MISO) link. There is vast amount of literature on cooperation in the physical layer [2–6], and there is increasing interest on network layer architectures supporting cooperative diversity [7–16]. Although improvements in single hop networks due to cooperative diversity has been studied, with many diverse examples [7–11] showing significant performance improvements, the literature on multi-hop cooperative protocols is still limited.

A common approach in the literature for incorporating cooperative diversity in multi-hop networks is to employ cooperation on already discovered and established routes. For example, in [2,12], cooperation is exploited to mediate an unreliable single hop link on the non-cooperative route, such that the original link is kept but its quality is improved by cooperative transmissions of the neighbors. On the other hand, in [13,14], an opportunistic v-MISO link is formed only when a link fails. As opposed to the schemes that consider single link improvements within non-cooperative routes, in [15,16], the objective is to improve the end-to-end performance of a route by utilizing cooperative (v-MISO) links in lieu of multiple links, and obtain a route with v-MISO links based on a non-cooperative route. Consequently, the existing schemes do not make use of all the route alternatives that can be realized for end-to-end communication between a source–destination pair. Furthermore, in these schemes, the number of relays participating in cooperation is fixed due to the fixed dimension of the underlying distributed space–time code (DSTC). Moreover, realization of cooperative diversity requires extra messaging for cooperative set selection and actuation, and under realistic wireless network scenarios, the throughput of the aforementioned systems will further degrade. This automatically raises the problem of how to select and actuate the relays in a decentralized, distributed fashion without obliterating the benefits of cooperation.

A cooperative routing scheme that circumvents the relay selection and actuation problem by use of opportunistic large arrays (OLA) [17] at the physical layer has been presented in [18]. OLA relies on the idea that each node accumulates energy from multiple transmissions of a packet, and relays this packet when the accumulated energy is above a predetermined threshold. However, the authors of [18] consider a perfect medium access control (MAC) protocol, which provides flawless coordination among the nodes, while packets are routed through the network. Furthermore, although OLA can be favorable for network flooding, its operation for unicast routing is problematic without an appropriately designed MAC protocol. If transmissions are not coordinated via a MAC protocol, OLA can result in multiple nodes transmitting different packets at overlapping periods, resulting in significantly degraded system performance.

The proper design of multi-hop cooperative protocols with cooperative diversity involves optimizing the behavior and performance of various layers jointly. In this paper, we propose a cross-layer cooperative network architecture that involves *cooperative flooding* and *cooperative forwarding* mechanisms for packet forwarding, and *Routing-Enabled Cooperative Medium Access Control (RECOMAC) protocol*, which facilitates these mechanisms by incorporating physical, MAC and routing layers. Our cooperative architecture exploits randomized coding, namely, Randomized Distributed Space–Time Codes (RDSTC) [19] at the physical layer. Randomized coding alleviates relay selection and actuation mechanisms, as a specific antenna index is not allocated per relay, and therefore the burden of coordination among the relays is reduced. In our cooperative forwarding mechanisms, the coded packets are forwarded from a cooperative set to a consecutive cooperative set in the direction towards the final destination, while no messaging is required among the relays of a cooperative set.

The main features of the proposed architecture and our contributions are as follows: (i) Physical layer cooperation via RDSTC is incorporated into a network setting by designing MAC and routing functions jointly, resulting in an architecture and a cross-layer protocol. (ii) In this architecture, cooperative sets are opportunistically formed on the fly in a distributed fashion, without the need for explicit relay selection and actuation, resulting in robust cooperative links and routes. (iii) The end-to-end route is defined as a series of *regions* in which the relays reside, as opposed to a string of predetermined nodes used in existing methods [15,16,18]. (iv) The progress of the packets towards the direction of the final destination enables connectivity even for sparse networks. (v) Through the RECOMAC protocol, the routing layer functionality is submerged into the MAC layer such that the MAC packet exchanges are exploited for route formation. (vi) In RECOMAC messaging overhead due to route discovery and establishment is minimal, since a prior non-cooperative route is not required before cooperative transmissions, as opposed to the schemes [15,16]. (v) via detailed simulations, the performance of proposed architecture and RECOMAC protocol is evaluated in terms of end-to-end throughput and end-to-end delay as well as overhead, in comparison to the performance of a non-cooperative, conventional architecture using well known MAC (IEEE 802.11) and ad hoc routing (AODV) protocols. It is shown that RECOMAC provides significant improvements in end-to-end throughput and delay with much smaller overhead under static and mobile