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Exploiting spatial multiplexing and reuse in multi-antenna wireless ad hoc networks ☆

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ABSTRACT

Efficient exploitation of multiple antenna capabilities in ad hoc networks requires carefully designed cross-layer techniques. The work presented in this paper provides a medium access control (MAC)/physical cross-layer scheme for ad hoc networks to address several of the challenges involved in cross-layer design. Multiple antenna systems can be used to increase data rate by spatial multiplexing, that is communicating multiple parallel streams, and to increase spatial reuse by interference suppression. Our proposed scheme, called HYB, exploits both spatial multiplexing and reuse so a receiver node can receive multiple simultaneous data streams from a desired transmitter while suppressing interference from other transmitters in the neighborhood. HYB partitions the available degrees of freedom in the antenna array between spatial multiplexing and reuse which allows the user to obtain different performance characteristics. The applicability of HYB spans across all wireless environments, including line-of-sight and dense multipath scenarios.
Simulations demonstrate the significant performance gains and flexibility offered by HYB. The simulation results also offer key insights into the multi-antenna resource allocation problem in ad hoc networks based on traffic patterns and network/transport layer protocols, and consequently provide guidelines for network configuration/management. We show that throughput increases when the degrees of freedom allocated to spatial multiplexing increases, while fairness increases when the degrees of freedom allocated to spatial reuse increases.

1. Introduction

Due to advances in technology it is now possible to build a wireless ad hoc network in which each node has more than one antenna [1–3]. Such networks can, in principle, support higher data rates than conventional single antenna based wireless ad hoc networks. However, integrated medium access and physical layer schemes are needed to fully exploit the additional capabilities of these multi-antenna networks. This paper proposes one such cross-layer scheme called HYB, which is an abbreviation for “hybrid”. The salient feature of HYB is that it seamlessly combines two different methods of exploiting multi-antenna capabilities for achieving higher data rates. The first method, called *spatial multiplexing* [4], involves concurrently transmitting multiple data packets between a pair of communicating nodes to increase the data rate. The second method, called *spatial reuse* [5,6], relies on interference suppression to increase the spatial reuse of the wireless medium by allowing multiple pairs of communication in the same neighborhood.

Methods to exploit multiple antennas to achieve higher spatial reuse [7–9] and to achieve higher data rates in a

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link-to-link scenario are well-known in the literature (see [10–12]). However, the lack of a centralized infrastructure in ad hoc networks renders the application of such methods to ad hoc networks challenging. For example, the following issues arise:

- The protocol must obtain and distribute channel information since most physical layer multi-antenna schemes rely on channel information either at the receiver or at both the transmitter and the receiver.
- Channel information has to be updated on a timely basis due to the dynamic nature of ad hoc networks.
- The most natural way to exchange channel and other relevant information is by using control information messages. Control messaging must be made extremely reliable if this approach is taken.
- It is desirable to support both spatial reuse and multiplexing so that each node retains maximum flexibility in allocating its resources.
- The protocol must be able to adapt to different wireless environments.

This list, while not exhaustive, illustrates many of the key challenges in exploiting multiple antennas in ad hoc networks. The protocol presented in this paper addresses the challenges listed above.

Considerable recent work has focussed on using antenna arrays for directional transmission/reception to improve spatial reuse/energy efficiency. Many authors have proposed cross-layer designs involving modifications to the IEEE 802.11 MAC protocol for use with multiple beam directional antennas [2,3,6,13–18]. The dominant theme is design of efficient information exchange at the MAC/higher layers to enable exploitation of the antenna array. However, these approaches are based on directional transmission which imply an underlying assumption of line-of-sight (LOS) propagation. In multipath environments with significant angular spreads, which are common to ad hoc network applications operating in urban or indoor settings, LOS methodologies are likely to be ineffective.

MAC protocols for generic multiple input multiple output (MIMO) environments have been recently proposed in [19–22]. The work in [19] exploits the spatial-multiplexing and interference suppression capabilities of the array to schedule different multiple spatially-multiplexed link transmissions and ensure network fairness. This contribution is based on a physical layer abstraction – an implicit assumption that a mechanism to implement the spatial-multiplexing/reuse capabilities exists. However, implementing such a mechanism is not straightforward. In the present paper we propose a specific protocol for achieving spatial reuse and multiplexing.

In [20] we previously proposed a cross-layer protocol to enable spatial reuse in a flat-fading environment. Our present contribution differs in two ways: (i) a significant portion of the control overhead that ultimately limits the performance of the protocol presented in [20] is eliminated, and (ii) both spatial reuse and multiplexing are integrated. The authors of [21] consider an uncoordinated medium access framework with a closed loop channel estimation framework as opposed to the coordinated (IEEE 802.11 like) MAC framework considered with an open loop channel estimation framework considered in this paper. Further, the scheme in [21] assumes that the covariance of the interference remains unchanged during the course of the data communication which may not be the case if newer communications commence in the neighborhood while the data transmission is still active. Also the interference that a new transmission causes to an existing session is not considered. In contrast, the scheme proposed in this paper enables the receiver to adapt to changes in the interference while receiving a packet so as to maintain a certain SINR. In [22] the authors consider a scheduling protocol to exploit the spatial characteristics of the nodes and their quality of service states.

A key feature of HYB is that each node independently and seamlessly allocates the available degrees of freedom (DOF) associated with its multiple antenna capabilities to either spatial multiplexing or spatial reuse. A second distinguishing feature of HYB is that it is effective in a wide range of wireless environments, from line-of-sight environments associated with open terrain to rich scattering, multipath environments associated with urban and indoor applications. The maximum benefits of HYB are obtained under rich scattering or strong multipath conditions where spatial multiplexing is possible. However, HYB is also applicable to LOS or sparse scattering conditions without any modification. Under LOS conditions HYB uses all its DOFs for spatial reuse. Note that methods that assume directional transmission or LOS channels will fail in the presence of significant multipath. HYB offers a level of robustness not offered by previously proposed protocols since it is applicable to both multipath and LOS channels and integrates the spatial multiplexing and interference suppression mechanisms.

The effectiveness of HYB in exploiting the multi-antenna capabilities is shown through simulations. We simulate cross-layer effects in great detail using an integrated ns-2 [23] and MATLAB[1] platform. The results show that for practical traffic scenarios the best performance is obtained by allocating spatial degrees of freedom (DOF) to carefully balance spatial multiplexing and spatial reuse. Throughput increases when the DOF allocated to spatial multiplexing is increased, while fairness increases when the DOF allocated to spatial reuse increases.

The organization of this paper is as follows. The following section provides a brief review of the IEEE 802.11 MAC protocol and wireless communications over multiple antenna or MIMO channels. Section 3 describes the MAC and physical layer details of HYB. In Section 4 we present simulations, results, and discussions. We conclude in Section 5. Lowercase characters in bold face represent vectors while uppercase bold face characters represent matrices. The superscript H stands for the matrix conjugate transpose operation, and $\|\cdot\|$ stands for the Euclidean norm-2 operator.

2. MAC and physical layer review

At the medium access layer, HYB is similar in many respects to the well-known IEEE 802.11 [24] protocol.

[1] MATLAB is a registered trademark of The Math Works Inc.