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A quality of service aware cross-layer approach for wireless ad hoc networks with smart antennas

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ABSTRACT

Recent technological advances have led to a growing interest in multi-antenna wireless ad hoc networks in which each node has more than one antenna. This paper proposes a cross-layer approach called QoS-aware smart antenna protocol (QSAP) for such networks that assures quality of service (QoS) needs of applications with reduced energy consumption. The proposed scheme adaptively allocates the degrees of freedom present in the multi-antenna system at each node to reduce the transmit energy while meeting the QoS needs of the application. The effectiveness of the proposed approach is demonstrated through simulations. The simulations show that the cross-layer aspects of the proposed approach result in considerable energy savings compared to schemes which meet the QoS needs without the cross-layer interaction.

1. Introduction

Wireless ad hoc networks are expected to be an integral part of the next generation information infrastructure. In these networks, there are no central controllers, such as base stations, to coordinate access to the shared wireless medium. Instead, the nodes rely on distributed medium access protocols such as IEEE 802.11 [26] to coordinate access to the wireless medium. Until recently, a common assumption in medium access protocols for wireless ad hoc networks was that the nodes are equipped with a single omni-directional antenna. However, advances in technology have it made possible to consider using multiple antennas at each node. Multiple antennas have been used in point-to-point communication scenarios to combat the effects of multipath fading and multi-user interference to provide significant gains in link capacity (see, e.g., [12,18]).

The use of multiple antenna systems for improving the throughput and reducing the energy consumption in wireless ad hoc networks has been the focus of recent research [1,5,9,15,20,22]. In general, multiple antenna systems are used to preferentially transmit in the direction of the receiver, thereby reducing interference at other nodes, reducing energy consumption at the transmitter, and increasing spatial reuse.

Several recent papers propose modifications to the IEEE 802.11 MAC protocol for use with multiple beam antennas to improve network throughput [9,15]. Fundamental MAC problems of neighbor discovery in directional transmissions are studied in [20]. In [22,5], the focus is on obtaining energy efficiency using multiple antennas. The use of directional antennas to improve the efficiency of on-demand ad hoc network routing protocols such as ad hoc-on-demand-distance-vector (AODV) is studied in [14]. A MAC protocol based on angle-SINR table is proposed in [1] to provide each node information on the direction of ongoing communication sessions in the neighborhood. The scheme proposed in [4] exchanges directional transmission information

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using reservation packets. All of the above schemes are designed with the underlying assumption of line of sight environments. In contrast, the schemes proposed in [11,24] consider multipath environments. The authors of [24] sketch out MAC design considerations for optimizing network performance assuming antenna array processing capability at the physical layer. In [11], the authors propose a physical/MAC cross-layer scheme, which employs zero-forcing beamformers to enable a higher degree of spatial reuse in the network while reducing the average transmit energy consumption.

One of the key characteristics of multiple-input multiple-output (MIMO) systems is that there is clearly a fundamental trade-off between using the antenna array for throughput improvement or for energy conservation. The multiple degrees of freedom (DOF) provided by the antenna array can be used for interference suppression, thus enabling a higher number of simultaneous data stream transmissions, and hence higher network throughputs. Alternately, fewer streams can be exchanged, and the surplus DOFs may be used for "beamforming" to obtain higher signal-to-noise ratio (SNR) at receiver nodes, or, equivalently if SNR is kept constant, power control can be used to lower transmission power requirements [13,8]. Exploiting this inherent trade-off between throughput and energy is the key motivation for the work presented in this paper.

Quality of service (QoS) has been, thus far, conventionally associated with network layer protocols. However, maintaining a layered architecture may not be the most efficient method to implement QoS related functionalities in wireless networks. The rationale behind this statement lies in the fact that the dynamics of a wireless network, including higher layer performance metrics, is quite strongly tied to physical layer characteristics like channel state, neighbor states, transmission strategies, etc. This is a consequence of the shared nature of the wireless medium. The scheme, QSAP, presented in this paper integrates the network layer QoS functionality with the antenna array capability at the physical layer. QSAP is a distributed scheme that uses the network layer service requirements as a guiding metric for exploiting the throughput-energy trade-off inherent to multiple antenna systems. In other words, a node uses its current state with respect to its specified service requirements to decide how many DOFs it is willing to use to transmit a packet. If the node is lagging its QoS requirement, it uses a large number of DOFs to urgently dispatch the packet even in the presence of a larger number of interferers. If the node has exceeded its QoS requirements, it allocates fewer DOFs which causes it to wait until the number of interferers is small enough. Since, in general, fewer interferers result in less transmit power. QSAP is completely distributed and requires minimal overhead.

QSAP can be seamlessly integrated with most MAC protocols which use the antenna array to both suppress interference and thus increase throughput, and reduce transmit power by exploiting array gain. We consider two such protocols in this paper to demonstrate the benefits of QSAP. The first one, which we call MRATE (also known as CSMA/CA(k)), is based on spatial multiplexing with channel side information at the transmitter [7,16], and can be incorporated into the IEEE 802.11 framework for MIMO-capable networks. The second protocol that we consider is NULLHOC [11], which is a MAC/physical layer scheme for achieving increased spatial reuse in multipath environments. We present simulation results for the implementation of QSAP with MRATE and NULLHOC. We compare the performance of MRATE-QSAP and NULLHOC-QSAP implementations with that of MRATE-NETQ and NULLHOC-NETQ, respectively, where the service differentiation is implemented at the network layer independent of the MAC/physical layer. The NETQ approaches exploit the benefits of MIMO at the physical layer without any cross-layer interactions and our comparison illustrates the benefits of using a cross-layer approach. The results demonstrate that QSAP performs far better than the MAC/physical layer independent approaches. QSAP consumes significantly lesser transmission energy in achieving identical service differentiation. Further, the adaptive nature of QSAP allows it to cater to diverse network requirements and loads without the need for any intermediate tuning.

The rest of the paper is organized as follows. Section 2 provides a brief review of multi-antenna systems. Section 3 introduces the QoS framework used by the network layer. In Section 4 we present our adaptive allocation scheme, QSAP. We illustrate implementation of QSAP in Section 5. Simulation results for NULLHOC and MRATE implementations are presented in Section 6. We conclude in Section 7.

2. Multi-antenna model – the throughput-energy trade-off

Multiple antennas have recently emerged as a powerful technology for managing and exploiting the wireless propagation channel [12,18,2]. They can be used for directional transmission and reception to reduce transmit power requirements in LOS channels. In rich scattering environments, multiple antennas can be used to increase data transmission capacity by creating multiple non-interfering channels between the transmitter and receiver, commonly referred to as spatial multiplexing [25]. Furthermore, multiple antennas can be used by a receiver (transmitter) node to spatially discriminate between different transmissions (receptions) in the same radio neighborhood [10]. These methods are illustrated in the example below.

2.1. Spatial multiplexing

Consider a transmitter $T0$ and a receiver $R0$ with N antennas each. Under rich scattering assumptions the $N \times N$ narrowband MIMO channel matrix between $T0$ and $R0$ can be modeled as a matrix, $\mathbf{H}_{0,0}$, of random complex Gaussian coefficients with zero mean and unit variance [19]. This matrix models the multipath propagation characteristics between the antennas at $T0$ and $R0$. Knowledge of $\mathbf{H}_{0,0}$ can be used to design $N \times K$ transmit and receive beamforming matrices, $\mathbf{W}_T$ and $\mathbf{V}_R$, respectively, so as to effectively diagonalize the channel matrix $\mathbf{H}_{0,0}$, that is,

$$\mathbf{W}_T^H \mathbf{H}_{0,0} \mathbf{V}_R = \mathbf{D}, \qquad (1)$$