Spatial Reuse through Adaptive Interference Cancellation in Multi-Antenna Wireless Networks

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***Abstract*— Efficient medium access control in wireless networks has been a challenging task. While the IEEE 802.11 standard coordinates contention effectively, it severely limits the number of concurrent communications. This results in reduced throughput and efficiency. Recent research has focused on employing multiple antennas to increase throughput in a multipath environment by enabling multiple streams between a transmit-receive pair. In this paper we show that exploiting multiuser diversity to enable concurrent communications has certain advantages over multiple streaming. We propose a medium access control (MAC) protocol that uses adaptive interference cancellation with multiple antennas to increase network throughput and to provide better fairness, while requiring minimal change to the widely-deployed 802.11 MAC structure.**

I. Introduction

Wireless networks are becoming an integral part of the information infrastructure. Applications of wireless LANs (Local Area Networks) formed between laptops, PDAs etc. include conferencing, disaster relief and military operations. However, throughput in these networks is limited by the need to coordinate multiuser access to the shared wireless medium. Current medium access control (MAC) protocols like IEEE 802.11 [1] that allow a single communication in a contention region (region around a transmit-receive pair that overlaps with the transmission or sensing ranges of other nodes) are likely to be insufficient to meet the throughput demands of emerging applications and systems.

Devices equipped with multiple antennas have been envisioned as a means to increase throughput in wireless networks. Antenna arrays can have either a pre-determined beampattern such as in switched or steered directional arrays, or adapt their beampattern in a smart fashion by changing the weighted combination of signals from the multiple antennas. Refs. [2]–[6] present MAC protocols that utilize fixed-beam directional antennas to concentrate the energy in a particular direction, thus enabling simultaneous non-interfering directed communications. While these protocols work for a line of sight environment, practical scenarios are often characterized by rich scattering in which signals propagate along multiple paths between a transmit-receive pair. In multipath environments smart antenna techniques can allow multiple users, each coupling into the best spatial channel (as opposed to direction), to set up concurrent transmissions by canceling interference from other users. Alternatively, the linearly independent channels created by multipath can be used to send multiple data streams between a transmit-receive pair (spatial multiplexing). Reference [7] proposes a MAC protocol that utilizes controlled spatial multiplexing to ensure network fairness. Another MAC protocol that works for multipath but leverages on the interference cancellation capability of multi-antenna systems to enhance spatial reuse is presented in [8]. It uses deterministic nulling and thus requires knowledge of channels to the interferers and weights used by them. This necessiates extra control overhead and a separate control channel, and is able to suppress interference only from packets that can be decoded.

In this paper, we focus on developing a MAC protocol that employs adaptive interference cancellation to increase network throughput and fairness, while making minimal changes to the widely deployed 802.11 MAC structure. We model the physical and MAC layers in detail and compare our results to 802.11a and a spatial multiplexing based MAC with respect to the tradeoff of energy vs. throughput, and fairness.

Cross-layer design of MAC and physical layers is necessary to leverage the full benefits of multi-antenna systems for setting up concurrent transmissions in a wireless network. Resolution of multiuser contention for the medium and destination necessitates the need for an omni-directional control exchange before the beamformed data packet transmission. Thus we retain the 802.11 control structure of RTS (Request to Send) and CTS (Clear to Send) which additionally carry pilot symbols for estimating the channel state information (CSI) between the transmitter and receiver. After the control exchange, beamformed DATA and ACK transmission can take place. The transmitter uses the CSI for coupling into the best spatial channel between the source-destination pair, while the receiver minimizes asynchronous interference from other users by adapting its receive weights to achieve maximum SINR (Signal to Interference plus Noise Ratio). Another node can start its control exchange soon after the first node completes its RTS-CTS exchange, thus establishing concurrent DATA transmissions. This requires modifying IEEE 802.11 physical and virtual carrier sensing to sensing for only omni-directional packets and a modified network allocation vector (NAV), respectively. We defer the details of the scheme to a later section.

In this paper we also derive a bound on the maximum number of concurrent multiuser transmissions that can be established (Section IV) as a function of data rates. If a sufficient number of antennas are available, each user can further be allowed to send more than one stream. This can be done easily along the lines suggested in [7] or [9]. It should be noted that this would increase throughput but at the expense of additional energy. A combined interference cancellation-opportunistic streaming approach would degrade more gracefully than spatial multiplexing when the channel between a transmit-receive pair looses diversity.

The paper is organized as follows. Section II presents the physical layer processing required at the transmit and receive antennas to adaptively suppress interference and maximize SINR. Section III proposes a MAC layer that achieves multiuser coordination to enable setting up of concurrent communications. Section IV presents the simulation results and we conclude in Section V.

II. Physical Layer

A. Channel model

The wireless physical medium is modeled as a flat or frequency-independent Rayleigh fading model. In this model, assuming equal number of antennas N at each node, the channel between a pair of nodes is given by a $N \times N$ matrix $\mathbf{H}$ where H_{ij} represents the effective fading between the i^{th} transmit antenna and the j^{th} receive antenna. This model is appropriate for narrowband communication. Extensions to wideband environments will require conventional physical layer enhancements such as in [10]. We assume that there is rich scattering so that all channels are independent and $\mathbf{H}$ is full rank. We also assume that the channel is symmetric so that the receiver knows the transmit weights that are designed based on the channel estimate at the transmitter. [1] Further, it is assumed that the channel remains constant over a packet exchange (RTS, CTS, DATA, ACK). This ensures that the channel estimates from the RTS/CTS packets are valid for DATA/ACK transmission and reception.

B. Antenna Array Processing

The modulated DATA/ACK signal $s(t)$ to be transmitted is passed through a transmit antenna array or beamformer with a $N \times 1$ weight vector $\mathbf{w}_T$. Thus the received signal vector at the receiver antenna array in the absence of interference is given as

$$\mathbf{x} = \mathbf{H}^H \mathbf{w}_T s(t) + \mathbf{n} \tag{1}$$

where $\mathbf{n}$ denotes additive white Gaussian noise. In the presence of interferers, the received vector is modified as

$$\mathbf{x} = \mathbf{H}^H \mathbf{w}_T s(t) + \sum_{i \epsilon I} \mathbf{H}_i^H \mathbf{w}_i s_i(t) + \mathbf{n} \tag{2}$$

where the summation is over the number of other transmitting nodes or interferers. Here $\mathbf{w}_i$ and $\mathbf{H}_i$ represent the interferer's transmit weight vector and its channel to the receiver, respectively. The receiver uses a set of $N \times 1$ weights $\mathbf{w}_R$ to combine the antenna inputs $x_j(t)$ and obtain the reconstructed signal as

$$\hat{s}(t) = \sum_j w^*_{R_j} x_j(t) = \mathbf{w}_R^H \mathbf{x} \tag{3}$$

The gain to the signal $s(t)$ is thus given as $\mathbf{w}_R^H \mathbf{H}^H \mathbf{w}_T$.

C. Omni-directional Control Exchange

In the absence of CSI at the beginning of a communication, the RTS and CTS are transmitted omni-directionally. The RTS and CTS headers carry an identifier bit which indicates that the packet is an omni-directonal control packet. When idle, nodes listen for this identifier bit by decoding any signal that appears above the noise level at its receive array. If the omni-identifier bit is not detected in the header, the signal is identified as interference and whitened. The whitening prevents interference due to ongoing beamformed transmissions from disrupting the decoding of an omni-packet. The RTS/CTS headers also carry a pilot sequence that is transmitted using all antennas to enable the estimation of channels between the transmit-receive antennas using standard channel estimation methods [11], [12]. The receiver now uses the channel information for enhancing SINR by maximal ratio combining (MRC) [13] to receive the rest of the packet. This enables successful reception of the omni-packet despite interference from transmissions that may start during the packet.

D. Beamformed DATA and ACK Transmissions

- *Design of Transmit Weights*: DATA/ACK is transmitted by beamforming to couple the energy into the best spatial channel between the transmitter and receiver array, characterized by the largest singular value of the estimated channel matrix.

$$\mathbf{w}_T = \frac{1}{\sigma_1} \mathbf{u}_1 \tag{4}$$

  where σ_1 and $\mathbf{u}_1$ denote the largest singular value and associated left singular vector.
- *Design of Receive Weights*: The DATA/ACK receive weights are designed to maximize the received SINR:

$$SINR = \frac{\mathbf{w}_R^H \mathbf{R}_{ss} \mathbf{w}_R}{\mathbf{w}_R^H (\mathbf{R}_{ii} + \mathbf{R}_{nn}) \mathbf{w}_R} \tag{5}$$

  where terms $\mathbf{R}_{ss}, \mathbf{R}_{ii}$ and $\mathbf{R}_{nn}$ represent the correlation due to the signal, interference and noise, respectively. This expression can be reduced to a Rayleigh quotient form that is maximized by setting the receive weights to

$$\mathbf{w}_R = \mathbf{q}_{max} \tag{6}$$

  where $\mathbf{q}_{max}$ is the eigenvector associated with the largest eigenvalue λ_{max} of the matrix $(\mathbf{R}_{ii} + \mathbf{R}_{nn})^{-1} \mathbf{R}_{ss}$ [14]. With this choice of receive weights, a maximum SINR of λ_{max} is obtained. Notice that in the absence of interference, the receive weight $\mathbf{w}_R = \mathbf{v}_1$, the right singular vector associated with the largest singular value of the channel matrix, and provides a signal gain of 1 at the receiver.

[1] If the channel is asymmetric, the weights or estimated channel coefficients can be exchanged in the packet headers between a transmit-receive pair, incurring some extra overhead.

On receiving the RTS/CTS, the receiver designs its weights using the current sample covariance matrix $\hat{\mathbf{R}} = \hat{\mathbf{R}}_{ii} + \hat{\mathbf{R}}_{nn}$ and the estimated channel $\hat{\mathbf{H}}$. Note that the receiver knows $\hat{\mathbf{R}}_{ss} = \hat{\mathbf{H}}^H \mathbf{w}_T \mathbf{w}_T^H \hat{\mathbf{H}} \sigma_s^2$ since by assuming the channel is symmetric the receiver can calculate according to (4) the weights $\mathbf{w}_T$ the transmitter will use for sending the beamformed DATA/ACK packet. Also all transmitters use a fixed signal power, σ_s^2 that is known to the receivers.

- *Disallowing a Communication*: Based on the expected SINR as given by (5), the receiver calculates the transmit power scaling ratio r required at the transmitter to boost the received SINR to the desired level.

$$r = \frac{SINR_{desired}}{SINR_{expected}} \tag{7}$$

  If this ratio implies that the transmit power for the DATA/ACK will exceed the power bound - as would happen if the interference level at the receiver is too high or the channel between the receiver and transmitter is poor - the receiver decides not to send the CTS/DATA and disallows the communication. Otherwise, it sends the CTS/DATA containing r in the packet header.
- *Readjustment of Transmit Weights*: To meet the desired SINR at the receiver, the transmitter scales up its weights by a factor of $\sqrt{r}$ before transmitting.
- *Readjustment of Receive Weights for Adaptive Interference Cancellation*: While the transmitter uses a fixed set of weights, the receiver continuously adapts its receive weights based on a current estimate of the covariance matrix to maximize the SINR as new interferers come up and others go away. Standard algorithms like Least Mean Squares (LMS) or Recursive Least Squares (RLS) can be used to implement this update iteratively [14].

III. THE MAC PROTOCOL

In this section, we develop the medium access control (MAC) protocol required to enable concurrent multiuser communication by adaptive interference cancellation. Setting up a beamformed transmission requires channel knowledge between the transmitter-receiver pair. Acquiring CSI knowledge at the transmitter and resolution of multiuser contention for the destination necessitate an omni-directional control exchange prior to a beamformed transmission. This control messaging is done through the omni-directional RTS (Request to Send) and CTS (Clear to Send) exchange between nodes as in IEEE 802.11. After this control exchange, beamformed DATA and ACK can be sent. Thus our scheme is characterized by two kind of packets - omni-directional RTS, CTS and beamformed DATA, ACK.

To prevent corrupting the channel estimation, nodes need to maintain a modified NAV as in IEEE 802.11 that preempts nodes from initiating an RTS/CTS exchange for a 'sifs+CTS' duration once they hear an RTS. Since nodes are preempted for a smaller duration than the entire packet exchange, nodes get faster access to the medium. Further, to detect the medium as "idle" and initiate a new data exchange, nodes now only need to sense for an omni-directional packet as identified by a bit in the header (Section II). The IEEE 802.11 physical carrier sensing is therefore modified to omni-packet sensing. If a node senses an omni-directional transmission (physical carrier sensing) or its NAV value is greater than zero (virtual carrier sensing), it assumes that the medium is busy and defers from transmitting any potential omni-packets as in IEEE 802.11 CSMA/CA to avoid collision with the ongoing omni-packet.

A typical packet exchange occurs as follows. It is assumed that a node can't transmit and receive at the same time.

1. A node that has a packet to send to another node first sends out an omni-directional RTS (Request to Send) control packet if it detects the channel as idle. The RTS packet carries pilot symbols to enable channel estimation at the corresponding receiver. After sending the RTS, the node continues sensing for an omni-packet.
2. All nodes within hearing range of the source receive the RTS and update their NAVs for a 'sifs+CTS' duration. The destination estimates its channel to the source and the expected SINR of the DATA packet. It then calculates the transmit power scaling required to achieve the desired SINR. If this implies that the transmit power at the source will exceed the upper bound, the receiver disallows the communication and does not send the CTS (Clear to Send). Otherwise, a CTS is sent that contains the transmit power scaling ratio and pilot symbols for channel estimation at the source. The receiver then sets its weights based on the channel estimate and current correlation structure at its antennas to receive the beamformed DATA packet and maximize the SINR.
3. On hearing the CTS, the source estimates the channel to the receiver and sets its weight to couple into the best channel for DATA transmission. It scales up its transmit power by the scaling factor provided in the CTS and sends the DATA packet. The DATA packet header is modified to carry the transmit power scaling factor for ACK transmission.
4. The receiver receives the DATA packet while adapting its weights to maximize the SINR as some interferers come up and others go away. A beamformed ACK is sent by coupling into the best spatial channel and scaling the transmit power for ACK by the scaling factor contained in the DATA header.
5. Successful reception of the ACK packet completes a packet exchange. Both transmitter and receiver now back-off for a RTS+sifs+CTS duration to prevent collision with any currently ongoing omni-packet that may not have been heard to set the NAV appropriately.

Error correction codes are used for each packet. If an error is detected, the packet is dropped and no reply is sent. Thus CTS, DATA and ACK packet losses occur due to low SINR, while RTS packets may be lost either due to low SINR or a collision. Collisions and retransmissions are handled in the same way as in IEEE 802.11. Thus the MAC protocol required for implementing interference-adaptive nulling scheme is similar to IEEE 802.11, with slight modification of physical carrier sensing, NAV (virtual carrier sensing), and packet headers.

IV. Simulation Results

The proposed protocol was simulated using an integration of MATLAB [2] and *ns*-2, a discrete-event network simulator [15]. The physical layer is implemented in MATLAB, which provides a runtime feedback to the *ns* simulator that implements the MAC and higher layers, thus simulating the MAC/Phy cross-layer processing accurately and in detail.

The 802.11 MAC code in *ns* is modified to implement the receiver based adaptive interference cancellation protocol. Physical and virtual carrier sensing are implemented as detailed in Section III. The RTS and CTS structure is modified to carry pilot symbols of 10 bits/antenna, the length being chosen to bound the channel estimation error variance to 0.1 times the channel noise variance. In addition, the CTS and DATA headers also carry the transmit power scaling ratio factor for DATA and ACK transmission, respectively. MATLAB uses information from *ns* to update the correlation structure as a transmission begins and ends, modeling the interference and signal strength at each node. The transmit and receive weights are designed and updated for beamformed transmissions. Before sending a CTS, *ns* calls MATLAB to check whether the transmit power required for sending DATA based on the current interference level at the receiver exceeds the power bound. Reception of every packet in *ns* is also followed by a call to MATLAB to check if the SINR requirement is met.

The Rayleigh channel coefficient between transmit-receive antennas is modeled as a complex white Gaussian random variable with zero mean and a variance of 0.5 for each of the real and imaginary parts. The channel is assumed symmetric, and constant for a packet exchange. The channel from a transmitter and receiver to each other and to other nodes is updated before each new transmission.

We use the physical layer parameters as specified in 802.11a protocol and assume a transmissions rate of 54 Mbps. We also compare our results with 802.11a MAC. To ensure a fair comparison, the physical layer in 802.11a is also modeled and packets are dropped if the received SINR falls below the threshold of $7\,$dB as in our scheme. The transmission range of the nodes is determined by the omni-directional control messages with a signal power of 20 dB in the simulations. A packet size of 1000 bytes is used in the simulations, which corresponds to the maximum size allowed without fragmentation for UDP and TCP in the *ns* implementation.

The scenario we chose models a network with 20 static nodes, all within radio range of each other to allow maximum communications to be set up with worst case interference. Nodes are assumed to be equipped with $N = 4$ antennas unless otherwise mentioned. To explore the maximum throughput obtainable, a high-rate ($8\,$Mbps) UDP traffic is chosen so that nodes always have packets to send. Figure 1

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

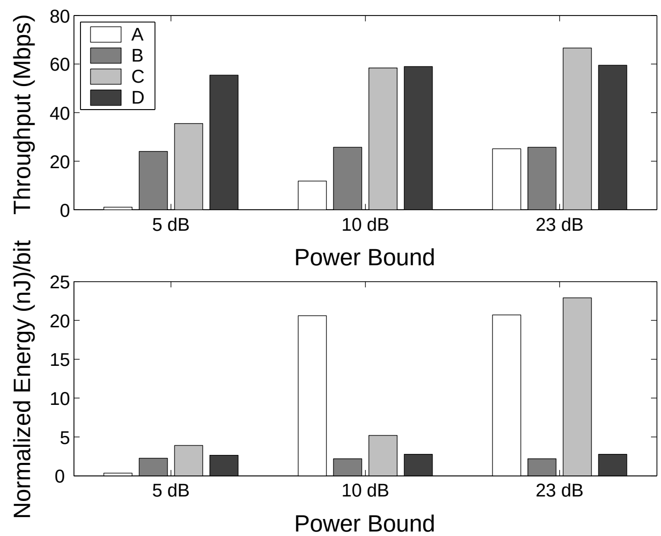

Fig. 1. Throughput gains and Normalized Energy consumed/bit (assuming unit signal power) for (A) single antenna 802.11a MAC, (B) multiple antennas used with 802.11a MAC, (C) spatial mulitplexing based MAC and (D) adaptive interference cancellation based MAC.

shows the throughput and energy consumed/bit with varying power bounds for 4 schemes - 802.11a MAC with single antenna (Scheme A), multiple antennas used for energy gains in a 802.11a MAC (Scheme B), spatial mulitplexing based MAC (Scheme C) and adaptive interference cancellation based MAC (Scheme D). The power bound of $23\,$dB corresponds to infinity in practice as no communications are disallowed due to power considerations in any of the schemes.

It can be seen that multiple antennas deployed with a 802.11a MAC (Scheme B) provide multipath diversity gains and hence energy savings over single antenna 802.11a (Scheme A). For low power bounds, the energy savings translate into increased throughput over Scheme A, however the maximum achievable throughput for Scheme B is same as for Scheme A (as shown by the case with no power bound). Schemes C and D allow for spatial reuse by allowing concurrent DATA exchanges, resulting in higher throughputs than A and B. With no power bound, the throughput with spatial multiplexing (Scheme C) is $66.6\,$Mbps, slightly higher than $59.5\,$Mbps for Scheme D. This is because sending mulitple streams between the same destination-source pair requires less contention for the medium, thus increasing medium utilization. However it uses successively weaker channel modes to transmit additional streams and hence the normalized energy/bit was found to be $22.9\,$nJ, as compared to $2.8\,$nJ for Scheme D. Adaptive interference cancellation (Scheme D) exploits multiuser diversity to set up concurrent transmissions, with each transmission done using the best spatial channel, and hence it provides energy savings as well as throughput gains. Thus spatial reuse by adaptive interference cancellation is capable of exploiting both multipath and multiuser diversity. As power bounds become more stringent, the proposed Scheme D provides large throughput gains while consuming energy

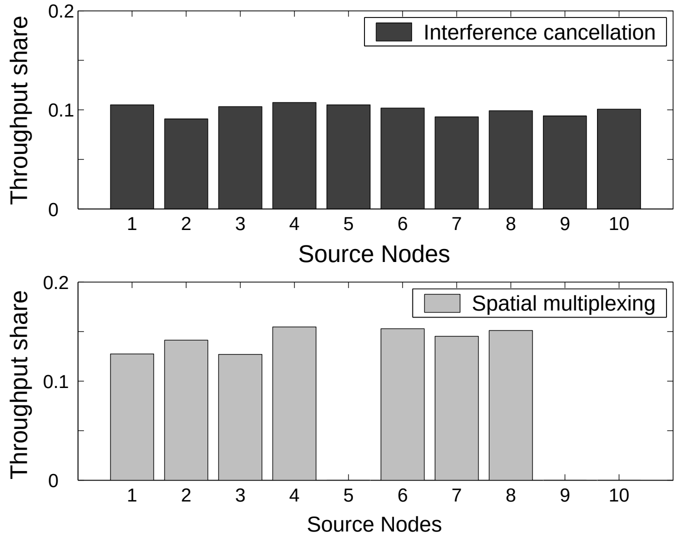

Fig. 2. TCP fairness for adaptive interference cancellation and spatial multiplexing. Notice that nodes 5, 9 and 10 are completely devoid access to the medium in spatial multiplexing.

comaprable to the other schemes.

The throughput gain for Scheme D over Scheme A indicates that a maximum of 2.3 simultaneous communications are set up in Scheme D, as compared to the theoretically estimated number of 4 (equal to the antennas, N). This can be explained by analyzing the structure of a packet exchange. Since the scheme allows another node to contend for the medium after an ongoing RTS-CTS exchange is complete, the maximum spatial reuse 'k' is given as:

$$\begin{aligned} k &= \min\left(N, \frac{\text{Total packet exchange duration}}{\text{difs+E[contention time]+RTS+sifs+CTS}}\right) \\ &\approx \min(N, 2.5) \text{for 802.11a (54 Mbps)} \\ &\approx \min(N, 8.7) \text{for 802.11b (1 Mbps)} \end{aligned}$$

Thus, in simulations, Scheme D enabled 2.3 concurrent communications as compared to the maximum possible 2.5. Further increase in throughput is possible by allowing each node to send more than one stream if its degrees of freedom, N, exceed this maximum number as suggested in [7] or [9], but at the expense of higher energy consumption.

We also study the behavior of spatial mulitplexing (Scheme C) and adaptive intereference cancellation (Scheme D) for adaptive sources like TCP in Fig 2. Since the congestion window is doubled with every successful packet exchange in TCP sources, with the ability to send multiple streams certain nodes gain complete access to the medium while others find the medium busy and are always backed off, e.g. nodes 5, 9 and 10 do not get access to the medium, while other source nodes get more than their fair share of 0.1. This phenomena is similar to the unfairness problem in IEEE 802.11 [16]. In contrast, since Scheme D increases spatial reuse by allowing mulitple user tranmissions through interference cancellation, we observe that all nodes get fair access to the medium. This is another desirable aspect of Scheme D.

V. Conclusion

In this paper we explore the use of multiple antennas to increase spatial reuse in a wireless network by adaptive interference cancellation. MAC layer modifications to IEEE 802.11 are proposed based on cross-layer design considerations that allow multiple simultaneous communications in multipath environments. Simulation results show that exploiting multiuser diversity by interference cancellation performs better than using multiple antennas with an 802.11a MAC or for sending multiple streams between the same source-destination pair, in terms of providing throughput gains *and* energy savings. Further, all users get fair access to the medium. We also show that, with increasing data rates, there is a limit on the maximum number of concurrent communications that can be set up. If the number of antennas exceed this number, they can be used for sending multiple streams, but at the expense of more energy.

Acknowledgements

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