NULLHOC : A MAC Protocol for Adaptive Antenna Array Based Wireless Ad Hoc Networks in Multipath Environments

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Abstract— **A medium access control (MAC) protocol for ad hoc networks of nodes with antenna arrays is presented. The antenna array is used for transmit and receive beamforming with the purpose of increasing spatial reuse by directing nulls at active transmitters and receivers in the neighborhood. In contrast to previous work with directional antennas, our approach is applicable to flat fading multipath channels, such as in indoors or in other rich scattering environments. The MAC protocol is designed to support the control information exchange needed to direct nulls toward other users involved in existing communication sessions. Knowledge of the channel coefficients between a transmitter or receiver and its neighbors is used to design transmit or receive beamformer weights that implement the requisite nulling. Simulations are used to demonstrate the improvements in throughput and transmit powers that are obtained in this approach relative to the conventional IEEE 802.11 MAC protocol.**

I. INTRODUCTION

Wireless ad hoc networks are expected to be an integral part of the next generation information infrastructure. Instead of relying on centralized controllers, the nodes in these networks must use distributed medium access protocols such as IEEE 802.11 [1] to reserve local access to the wireless medium. Until recently medium access control protocols were designed assuming single omni-directional antennas in mind. However recently multiple antennas have been shown as a feasible option for point-to-point links offering the potential for significant gains in link capacity, and can combat effects such as fading and multi-user interference (see, e.g., [2], [3]).

In this paper we present a medium access control (MAC) protocol termed NULLHOC designed for multipath multiple-input multiple-output (MIMO) communication channels. NULLHOC is based on using channel information to achieve energy savings and/or spatial reuse through nulling of ongoing communication sessions. The primary contribution of NULLHOC is a method for seamless and effective integration of the MAC and the physical layer resources provided by the antenna array. NULLHOC uses the knowledge of MIMO channels between antenna arrays at different nodes to design transmit and receive beamformers that achieve a specified gain to the desired node while nulling existing communications between other nodes. The pilot sequences needed to estimate the relevant channel coefficients and the additional information required for designing the transmit and the receive beamformer weights are incorporated into our MAC layer messaging. We show using simulations that NULLHOC provides both improved network throughput and energy efficiency relative to conventional IEEE 802.11 [1]. We analyze the effect of channel estimation errors on NULLHOC performance and show that it is robust to such errors in [4].

The problem of using the directional transmission capabilities of multiple antenna systems to improve the throughput and energy efficiency of wireless ad hoc networks has been a topic of recent research ([5], [6], [7], [8], [9], [10]). The dominant theme in the previous work is directional transmission, which implies an underlying assumption of line of sight propagation. Methods based on directional transmission are likely to experience difficulty in environments containing significant multipath, since then there will not be a single dominant path between transmitter and receiver. Many applications of ad hoc networks are for environments characterized by rich scattering. For example, a wireless ad hoc network in an indoor environment will experience substantial multipath effects due to the physical structure of the building. In this case directional beam steering is not likely to be effective. In contrast to previously proposed techniques, NULLHOC employs a multipath channel model that represents rich scattering and thus is effective in realistic physical environments.

The rest of the paper is organized as follows. The following Section describes the method for designing the transmit and receive beamformer weightings. In Section III, we define our proposed MAC protocol for coordinating multiple simultaneous communication links in a given neighborhood. Section IV describes our simulations and illustrates the throughput and power efficiency benefits of this approach. We conclude in Section V.

II. ANTENNA ARRAY PROCESSING

In this section we describe our algorithm for calculating the transmitter and the receiver weight vectors for each pair of nodes that wish to communicate, given channel characteristics. The notational convention is as follows. Lowercase boldface

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letters represent vectors while uppercase boldface letters represent matrices. A superscript ^{T} denotes matrix transpose operation while superscript ^{H} denotes complex conjugate transpose, and superscript $^{-1}$ denotes matrix inverse.

We assume that all channels have flat or frequency independent fading and that the fading or channel coefficients are known at the transmitter and receiver. Many space-time wireless communication methods rely on knowledge of channel coefficients (see e.g. [2], [11]). Our scheme uses pilot symbols transmitted along with the MAC layer control messages to estimate the coefficients using standard methods (see [12], [13]). Using a simple MIMO channel estimation model the variance of channel estimation error is given by $\sigma_E^2 = \frac{\sigma_n^2}{LE}$ where σ_n^2 is the channel noise variance, L is the length of the pilot sequence per antenna, and E is the transmit energy per symbol per antenna. We set the pilot sequence lengths to upper bound the variance of the estimation error given an assumed channel noise model and assuming the net pilot power to be constant.

Assuming N antennas at both the transmitter and receiver, we may represent the MIMO channel with an N by N matrix of channel coefficients $\mathbf{H}$ where the l, m element of $\mathbf{H}$, denoted as h_{lm}, represents the complex gain between the l^{th} transmitter antenna and the m^{th} receiver antenna. The characteristics of the channel matrix $\mathbf{H}$ are determined by the propagation characteristics of the physical channel. It can be shown that if the channel is line of sight and no scattering is present, then $\mathbf{H}$ is a rank-one matrix and is determined entirely by the relative directions of the transmitter and receiver arrays. On the other hand, in a dense scattering environment, $\mathbf{H}$ will be full rank with probability one and may be characterized as a random matrix. In the case of a single antenna, $N = 1$ and $\mathbf{H}$ is a scalar.

At the transmitter, the modulated signal $s(t)$ is passed through a transmit beamformer which sends a weighted version of the signal through each antenna. At the receiver, the received signals at each antenna are similarly weighted and summed to form a receive beamformer output $r(t)$ which is then demodulated to extract the bit stream. Let the N by 1 vector of transmitter weights be denoted as $\mathbf{w}_T$, and the N by 1 vector of receiver weights be denoted as $\mathbf{w}_R$. We may write the signal received at the i^{th} antenna as

$$x_i(t) = s(t) \sum_{j=1}^{N} w_{Tj} h_{ji}$$

The receive beamformer combines the $x_i(t)$ to obtain the beamformer output $r(t)$

$$r(t) = \sum_{i=1}^{N} w_{Ri} x_i(t)$$

Thus, $r(t) = s(t)\mathbf{w}_T^T \mathbf{H} \mathbf{w}_R$ and the complex gain experienced by $s(t)$ as a consequence of transmit beamforming, the channel, and receive beamforming is $\mathbf{w}_T^T \mathbf{H} \mathbf{w}_R$. By appropriately choosing the transmit and receive weights, we may ensure that the signal is received with a certain gain, or is perfectly nulled. Generally either $\mathbf{w}_T$ or $\mathbf{w}_R$ is given and we seek to design the other. We consider three cases, depending on whether the transmitter and the receiver are a desired communication pair or potentially interfere with one another.

TABLE I

RECEIVE BEAMFORMER DESIGN

1) Compute the effective channel vectors to other transmitters, $\mathbf{h}_k^T = \mathbf{w}_{Tk}^T \mathbf{H}_{k1}$, $k = 3, 4, \ldots, K+2$.
2) Compute the effective channel vector to the desired transmitter, $\mathbf{h}_2^T = \mathbf{w}_{T2}^T \mathbf{H}_{21}$. Note that since $\mathbf{w}_{T2}$ will be later designed at the transmitter to produce the desired signal to noise ratio at the receiver, we assume a default value of $\mathbf{w}_{T2} = (1/\sqrt{N})[\,1\ 1\ \cdots\ 1\,]^T$.
3) Build the N by $K+1$ matrix of channel vectors $\mathbf{X} = [\,\mathbf{h}_2\ \mathbf{h}_3\ \mathbf{h}_4\ \cdots\ \mathbf{h}_{K+2}\,]$.
4) Find $\hat{\mathbf{w}}_{R1}$ as the minimum norm solution to the set of linear equations $\mathbf{X}^T \hat{\mathbf{w}}_{R1} = \mathbf{c}$ where $\mathbf{c} = [\,1\ 0\ \ldots\ 0\,]^T$. This results in unit gain to the desired transmitter and zero gain to the other transmitting nodes.
5) Scale $\hat{\mathbf{w}}_{R1}$ to obtain unit norm receive weights $\mathbf{w}_{R1}$, i.e., $\mathbf{w}_{R1} = (\hat{\mathbf{w}}_{R1}^T \hat{\mathbf{w}}_{R1}^*)^{-1/2} \hat{\mathbf{w}}_{R1}^*$.

- If the receiver corresponding to $\mathbf{w}_R$ is the desired recipient of the message contained in $s(t)$ and $\mathbf{w}_R$ is fixed, we may choose $\mathbf{w}_T$ so that $s(t)$ is received with unit gain by requiring $\mathbf{w}_T$ to satisfy $\mathbf{w}_T^T(\mathbf{H}\mathbf{w}_R) = 1$.
- If the receiver corresponding to $\mathbf{w}_R$ is already involved in another communication link, then $\mathbf{w}_R$ is fixed and we may choose $\mathbf{w}_T$ so that the transmitter does not create interference at the receiver by requiring $\mathbf{w}_T^T(\mathbf{H}\mathbf{w}_R) = 0$.
- If the transmitter is already communicating with a different user using a fixed $\mathbf{w}_T$, and the receiver corresponding to $\mathbf{w}_R$ wishes to receive interference free communication from different transmitter, then we may null the contribution of $\mathbf{w}_T$ at the receiver by requiring $\mathbf{w}_R$ to satisfy $(\mathbf{w}_T^T \mathbf{H})\mathbf{w}_R = 0$.

In general multiple constraints of this type are used to design the transmit and receive beamformers. Knowledge of the active transmitters in the neighborhood of the receiver is used to design the receive weights at a given node, while knowledge of the active receivers in the neighborhood of the transmitter is used to design the transmit weights. The MAC protocol given in the following section allows each node to keep track of active transmitters and receivers in its neighborhood and also accommodates distribution of the required transmit and receive weights.

We now consider design of the receive and the transmit beamformers to satisfy multiple constraints simultaneously. Let $\mathbf{H}_{ij}$ be the channel matrix between the i^{th} transmitter and j^{th} receiver.

Table I describes the design of receiver weights so that node 1 can receive a transmission from node 2 without receiving interference from nodes $3, 4, \ldots, K+2$, which are currently transmitting to other users with weights $\mathbf{w}_{Tk}$.

Note that if $K+1 > N$ and the channel vectors are linearly independent, then there are not enough degrees of freedom in $\mathbf{w}_{R1}$ to obtain unit gain to the desired transmitter while nulling K other transmitters. Thus, the receiver at node 1 can null at most $N-1$ other transmitters. If $K+1 \leq N$ and $\mathbf{c}$ lies in the space spanned by the columns of the matrix $\mathbf{X}^T$ defined

TABLE II

TRANSMIT BEAMFORMER DESIGN

1) Compute the effective channel vectors to other receivers, $\mathbf{h}_m = \mathbf{H}_{1k}\mathbf{w}_{Rk}$, $k = 3, 4, \ldots, K + 2$.
2) Compute the effective channel vector to the desired receiver, $\mathbf{h}_2 = \mathbf{H}_{12}\mathbf{w}_{R2}$. In this case we assume $\mathbf{w}_{R2}$ is already designed using the receive beamformer design procedure described above.
3) Build the N by $K+1$ matrix of channel vectors $\mathbf{X} = [\ \mathbf{h}_2\ \mathbf{h}_3\ \mathbf{h}_4\ \cdots\ \mathbf{h}_{K+2}\ ]$.
4) Find $\mathbf{w}_{T1}$ as the minimum norm solution to the set of linear equations $\mathbf{X}^T\mathbf{w}_{T1} = \mathbf{c}$ where $\mathbf{c} = [\ 1\ 0\ \cdots\ 0\ ]^T$. This results in unit gain from node 1 to node 2 and zero gain to the other receiving nodes.

in step 3, then the design constraint in step 4 can be satisfied exactly. In general, the channel vectors are expected to be linearly independent in rich scattering environments because of the random nature of the channel matrices. The scaling in Step 5 ensures that the transmitter is responsible for achieving the desired signal to noise ratio (SNR) by forcing the white noise gain at the receiver ($|\mathbf{w}_R^T\mathbf{w}_R^*|^2$) to be unity. Note that gain at the receiver cannot increase the SNR since receiver gain has equal effect on both signal and noise.

Table II illustrates transmit beamformer design assuming node 1 wants to transmit to node 2 without causing interference at nodes $3, 4, \ldots, K + 2$, which are receiving other transmissions with receive weights $\mathbf{w}_{Rk}$, $k = 3, 4, \ldots, K + 2$. The transmit weights may be scaled by a constant to produce the desired SNR at the receiver. As in receive beamformer design, the transmitter at node 1 can direct nulls toward at most $N - 1$ other receivers.

The transmit power required to produce unit signal strength at the receiver corresponds to $\mathbf{w}_T^T\mathbf{w}_T^*$. In the unusual event that $\mathbf{h}_2$ is nearly linearly dependent with $\mathbf{h}_k$, $k = 3, 4, \ldots, K + 2$, or, that $|\mathbf{h}_2|$ is very small (Table II, Step 2), the corresponding weights $\mathbf{w}_{T2}$ will have large norm, which translates to large transmit power. As the number of null constraints increases at either the transmitter or the receiver, the norm of the transmit weights generally increases and consequently additional transmit power is required. In the case of a single antenna, $\mathbf{H}_{12}$ is a scalar and the transmit power required to achieve unit signal strength at the receiver is $|\mathbf{H}_{12}|^{-2}$, so large transmit power is required when the channel experiences deep fades, that is, when $|\mathbf{H}_{12}| \approx 0$.

In our approach, the channel coefficients are estimated during the exchange of control messages just prior to start of a data packet transmission. We assume that the channel is approximately constant during the exchange of control messages and the corresponding data and acknowledgment packet transmissions.

III. THE NULLHOC MAC PROTOCOL

The NULLHOC protocol for our antenna array scheme has the responsibility of disseminating information regarding the weight vectors of the active nodes by means of control messaging. Prior to data exchange between a transmitter-receiver pair, the receiver first calculates its weight vector to null interfering transmissions in the neighborhood using the methods given in the previous section. These receiver weights are conveyed to the transmitter. The transmitter then calculates its weights to null active receivers in the neighborhood and to obtain unity gain to the desired receiver. Lastly, the receiver and the transmitter convey their selections of weight vectors to all their respective inactive and receiving neighbors.

NULLHOC divides the total wireless bandwidth B at each node into two orthogonal channels using any standard frequency division or code division method : a Data Channel (DC) and a Control Channel (CC). The bandwidth allocated to the CC is αB, where $0 < \alpha < 1$ is a design parameter dependent on the degrees of freedom available and the network topology. NULLHOC is based on the following two physical properties.

1) A node can receive packets on the DC and CC concurrently.
2) When a node is transmitting on the CC or DC, it cannot receive a packet on the other channel.

The division of the wireless bandwidth into a CC and a DC is essential for our protocol. It gives each node increased capability for tracking other communications in the neighborhood. Since we assume a node cannot transmit and receive concurrently on CC and DC, our scheme does not rely on out-of-band control signaling. This differs from the approach in [14].

The NULLHOC protocol uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) based scheme on the CC to obtain access to the DC. In most cases, no collisions are expected on the DC. Suppose node a has a data packet for a neighboring node b. The access rights to the DC are obtained through the following 3-message exchange sequence. Node a first sends a Request-To-Send (RTS) control message addressed to b on the CC. If node b is willing and able to receive the data packet from a, it responds with a control message Clear-To-Send (CTS) addressed to a on the CC. Then, node a reserves the access right to the DC by sending a Data-Send (DS) control message addressed to node b on the CC. Node a then transmits the data packet on the DC. If the data packet is received correctly by node b, then its responds with an ACK packet addressed to a on the DC. Timeouts are used to recover from situations when an expected response is not correctly received in a timely fashion. When a timeout occurs, the ongoing exchange is aborted and the process is repeated later.

The message component of the RTS/CTS/DS exchanges can be transmitted using a single omni-directional antenna or by using multiple antennas and simple space-time coding (see, e.g. [15]). Space-time coding increases the robustness of the control messaging to deep fades in the channel. The pilot component of the RTS/CTS exchange involves all antennas. All the transmissions on the CC are omni-directional and are made at constant power.

In NULLHOC, nodes learn about the ongoing communications in their neighborhoods by monitoring the CC. Nodes that overhear either RTS, CTS, and/or DS note down the details of the corresponding communication. Note that a node cannot hear RTS, CTS or a DS while it is transmitting. If a node transmits a DATA packet without being aware of an ongoing transmission, then it corrupts reception at other nodes. To alleviate this possibility, all nodes wait for a fixed duration after finishing their transmission before they are allowed to initiate a new communication.

The messages exchanged on the CC include the antenna weights being used. For instance, a transmitter node includes the antenna weights that it will use to receive the ACK in the RTS message. Similarly, the receiver node also includes the antenna weights that it will use to receive the DATA packet and the antenna weights that it will use to transmit the ACK in the CTS message. Finally, the transmitter advertises its antenna weights for data transmission in the DS. The estimated duration of the communication is also included in these control messages. The transmission of the antenna weight information enables the transmitter to become aware of the receive antenna weights to be used by the corresponding receiver.

Finally, the nodes must know the channel coefficient matrices to the neighboring nodes. Our approach to estimating the channel coefficients is to include pilot or training symbols as part of the RTS and CTS control messages. Any node that hears an RTS or CTS may then estimate and store the corresponding channel coefficients. We assume that the CC and DC have the same channel coefficients, that the channels are reciprocal and that the channel coefficients are approximately constant over the time scales required to transmit a DATA packet on the DC. The impact of errors in estimating the channel coefficients are studied in [4] and are omitted here for the lack of space.

IV. SIMULATION RESULTS

In this section we present simulation results characterizing the performance of NULLHOC relative to IEEE 802.11 in different scenarios. Our realization of NULLHOC in ns-2 [16] implements every detail of our protocol as explained in the earlier sections. Furthermore we implemented a mechanism that enables ns-2 and MATLAB[1] to run concurrently and exchange information at runtime.

For performance evaluation, we compute normalized throughput as follows. Let M be the total number of bits received successfully on the DC, T be the total simulation time and L be the link bandwidth. Then the normalized throughput is taken as $M/(T * L)$.

For a given channel realization the power required for a particular transmission is the square of the norm of the antenna weight vector at the transmitting node (see Section II). We computed the average energy consumed per bit by dividing the total energy consumed by the total number of data bits transmitted over several random realizations of the channel. To qualitatively characterize the performance of NULLHOC, we compute the energy savings per bit transmitted with NULLHOC relative to IEEE 802.11. In the plots, we express the normalized energy savings per bit in decibels. NULLHOC requires more energy on the CC than 802.11 because of increased lengths of control message sequences.

One of the key inputs for NULLHOC is the fraction of link bandwidth (α) allocated to the CC. The fractional bandwidth required by the CC is strongly dependent on the number of antennas so we used simulations to identify the value of α that approximately maximized normalized throughput. The results therefore characterize the peak throughput that can be achieved with NULLHOC for the specific scenario. Note that, since the total bandwidth allocated to the CC and DC is set equal to the link bandwidth for IEEE 802.11[2], throughput gains seen in our approach are not due to having out-of-data-band control message exchanges - in contrast to [14].

Our simulations assume a rich Rayleigh scattering environment. We model the channel coefficients for any given transmitter-receiver antenna pair at a particular time instant as a Gaussian random variable with zero mean and a variance of 0.5 for each of the real and the complex parts statistically independent of the other coefficients. At the MAC layer, we assume that a node always has a packet for each node within its radio range. The lengths of the RTS/CTS/DS packets were set based on the number of antennas. RTS/CTS include basic header information as in IEEE 802.11, weight vector information (2 bytes per complex weight), and a stream of pilot sequence bytes whose length is chosen to bound the estimation error variance at $0.1\sigma^2$, where σ^2 is the channel noise variance. The DS is a packet specific to our protocol and it contains the source and the destination addresses in addition to the transmit weight vector of the source. We consider a typical wireless ad-hoc network scenario and we run two sets of simulations for packet sizes 512 and 1024 bytes. In both our NULLHOC and IEEE 802.11 simulations we set the transmit power upper bound to be 30 dB.

The scenario models a network with 100 static nodes uniformly distributed across a 750x750 grid[3]. The radio range of each node was set to a radius of 250 grid points. Fig. 1 shows the normalized throughputs for IEEE 802.11 and NULLHOC with different numbers of antennas. Due to spatial reuse, there can be more than one concurrent communication in IEEE 802.11. Consequently, the normalized throughput for IEEE 802.11 is greater than 1.0. Observe that, the normalized throughput of NULLHOC mostly increases with the number of antennas per node. There is an improvement for every additional antenna (when number of antennas is less than six). However, because the control overhead increases with an increasing number of antennas the throughput starts to saturate as we increase the number of antennas beyond six. In this scenario, throughput begins to drop when the number of antennas exceeds seven. The saturation point is reached earlier with smaller packet sizes because of the increase in proportion of the control overhead.

The energy savings per bit relative to IEEE 802.11 are shown in Fig. 2. The significant savings on the DC is because

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

[2] In our IEEE 802.11 simulations, the entire link bandwidth is available for control and data message exchanges.

[3] The results are averaged over several such random distributions.

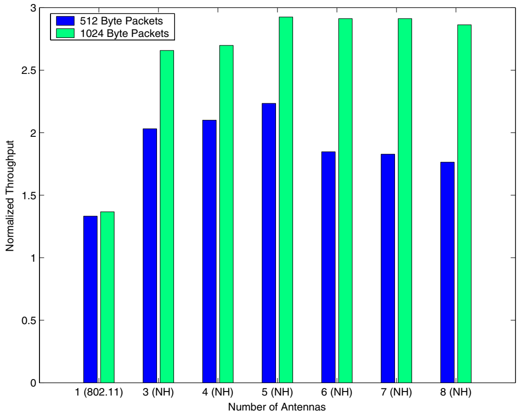

Fig. 1. Comparison of NULLHOC Throughput with 802.11 for 2 different Packet Sizes.

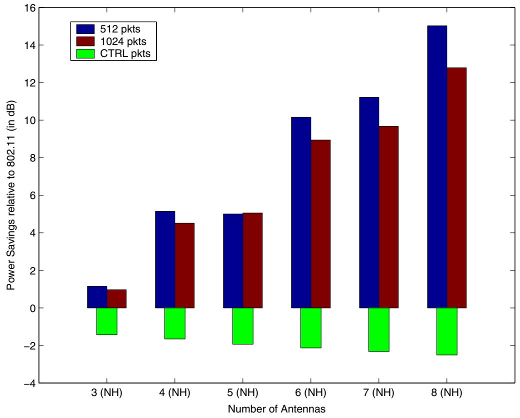

Fig. 2. Average energy saved per bit transmitted on the DC (positive bars) and the CC (negative bars) for NULLHOC relative to 802.11.

the number of nodes in each node's radio neighborhood is such that all available degrees of freedom are not always used to null the other ongoing communications. Degrees of freedom not used for nulling are used by the node to reduce transmission energy. The negative bars in the figure show the additional energy consumed by NULLHOC on the CC due to the need to transmit longer control message sequences. Note that aside from the 3 antenna case, NULLHOC performs substantially better than 802.11 in terms of energy efficiency (up to 12.5dB net savings per bit). As before, drops in throughput due to decreased packet size is offset by increased energy savings.

V. CONCLUSION

In this paper, we propose a scheme for exploiting adaptive antenna arrays in wireless ad hoc networks. Unlike most of the existing work in this area, the scheme in this paper is designed for environments characterized by multipath propagation between the nodes in the network. The proposed scheme directs nulls to other nodes to allow more concurrent data transmissions in a neighborhood. A medium access protocol, NULLHOC, which supports the information exchange necessary for directing the nulls is described in the paper. An integrated implementation of ns-2 and MATLAB is used to obtain simulation results comparing the performance of the proposed scheme with IEEE 802.11. Our results show that NULLHOC provides up to a factor of two increase in throughput relative to IEEE 802.11 and that the throughput gains tend to saturate as the number of antennas increase due to increased control overhead. However, very large reductions in the energy required per bit are obtained with NULLHOC for scenarios in which there are degrees of freedom not used for nulling. The energy savings increase as the number of degrees of freedom increase and offer a compelling rationale for using a multiple antenna protocol such as NULLHOC that exploits channel knowledge.

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