# MIMOMAN: A MIMO Mac Protocol for Ad Hoc Networks*

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**Abstract.** Multiple-Input Multiple-Output (MIMO) antenna systems present a radical way to improve the performance of wireless communications. Such systems can be utilized in wireless ad hoc networks for improved throughput in several ways. A straightforward way is to regard the MIMO system just as a new link layer technology that provides a higher data rate. In this way, MIMO systems can be integrated with legacy Media Access Control (MAC) protocols such as 802.11 DCF. Recently, a few studies have proposed MAC protocols leveraging the advantages of MIMO systems in a different way. Those new MAC protocols enhance the network throughput by allowing simultaneous multiple communications at a lower rate rather than a single communication at a higher rate in a single collision domain. In this paper, we present a new MIMO MAC protocol for Ad hoc Networks namely MIMOMAN. MIMOMAN tries to further increase the network throughput by combining the two approaches, i.e., allowing simultaneous multiple communications at a higher data rate. It is beneficial especially in a heterogeneous setting where the number of antennas installed on each node varies. As a part of the protocol, MIMOMAN also suggests a new beamforming algorithm that allows spatial reuse among spatial multiplexing MIMO links. We investigate the performance of MIMOMAN through a simulation study.

## 1 Introduction

One of the most interesting trends in wireless communications in recent times is the proposed use of multiple-input multiple-output (MIMO) systems [2]. A MIMO link employs an array of multiple antennas at both ends of the link. The use of multiple antennas at both transmitted and receiver provides enhanced performance over diversity schemes where either the transmitter or receiver, but not both have multiple antennas. MIMO systems can be utilized in ad hoc networks for improved network throughput in several ways. The most straightforward approach is to regard the MIMO link just as a link with higher data rates. MIMO

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systems can increase the data rate (or capacity) of a wireless link by the factor of $N$ where $N$ is the number of antennas without increasing transmit power or bandwidth. The most well-known technique is called spatial multiplexing (SM). In a SM-MIMO configuration, the incoming data is demultiplexed into $N$ distinct streams and transmitted out of $N$ antennas at the same frequency, with the same modulation, and with the same signal constellation. The approach, viewing MIMO systems as a new link-layer technology, does not require any support from upper layers thus conventional protocols such as 802.11 DCF MAC can run atop them without any modification. The network performance enhancement comes only from the faster links. Proposals for the emerging standard IEEE 802.11n follow this approach [14].

Recently, a few studies [8, 7] have proposed another way of exploiting MIMO systems in ad hoc networks. The MAC protocols proposed in [8, 7] exploit the beamforming [6] capability of MIMO systems and improve the network throughput by allowing multiple simultaneous communications at a lower rate instead of having one higher rate communication at a time. This approach is similar to that taken by MAC protocols developed for directional antennas [1, 4, 10] in that they facilitate spatial reuse, whereby multiple transmissions can take place simultaneously in the same collision domain [3]. The main difference is their operating environment. Directional transmission requires line of sight propagation. Indoor and urban outdoor environments are typically rich in scattering and possible line of sight blocking, multi-path conditions are prevalent. MIMO systems exploit multi-path propagation to provide higher total capacity. The rich scattering environment in fact is a much more realistic condition in indoor and urban outdoor networks.

The two approaches increase the network performance in very different ways. The first approach is increasing the link capacity using techniques such as spatial multiplexing and the second is enhancing spatial reuse among nodes. In this paper, we attempt to further increase network throughput by harnessing both techniques: beamforming to enhance spatial reuse among nodes and spatial multiplexing to increase link capacity using spatial multiplexing. We present a new MIMO Mac protocol for Ad hoc Networks, MIMOMAN, at the heart of which is a new beamforming algorithm that allows spatial reuse among spatial multiplexing MIMO links. This is beneficial especially in a heterogeneous setting where the number of antennas installed on each node varies. Antenna heterogeneity itself is an issue in MIMO based wireless networks. Beside the fact that commercial MIMO products are expected to vary in the antenna setting, considering the applications of ad hoc networks it is always better in general for protocols to tolerate as many kinds of heterogeneity as possible without compromising other important facts. Our cross-layer, joint PHY/MAC solution to the antenna heterogeneity problem benefits from it rather than tolerates it.

The main contribution of this work is a fully distributed MAC protocol that exploits SM-MIMO links and cross-layer techniques to enable spatial reuse among them. MIMOMAN provides a methodology with which nodes can identify interferers and acquire channel information at each transmitter and receiver pair to implement transmit and receive antenna beamforming that achieves spatial multiplexing while at the same time nulling of co-existing, potentially interfering transmitter and receiver pairs. From a communications theoretic point of view, the contribution of MIMOMAN is the first proposal of the beamforming algorithm that enables spatial reuse among spatial multiplexing links in ad hoc networks. The main advantage of MIMOMAN with respect to conventional 802.11 DCF style MAC is that it allows high-powered nodes to utilize residual capacity of the wireless channel thereby increasing overall capacity of a network.

Another recent study [13] proposed a framework for utilizing MIMO systems in ad hoc networks. While our focus is a realistic MAC protocol design, its focus is rather a general theory in that it formulates the MIMO antenna utilization problem in ad hoc networks as a network-wide optimization problem and graph-coloring based solution is proposed.

The rest of the paper is organized as follows. We describe MIMOMAN in Section 2. Section 3 details our evaluation of the performance of MIMOMAN using simulation. Finally, Section 4 concludes the paper. We assume that readers are familiar with MAC protocols such as 802.11 DCF. This paper can be easily read with basic knowledge of communications theory but we expect that some knowledge of Linear Algebra suffices for understanding the protocol.

## 2 Protocol Description

In this section we describe details of the MIMOMAN protocol. We first consider a restricted case of the protocol termed bMIMOMAN which runs on the special type of MIMO system called beamforming MIMO. bMIMOMAN allows multiple simultaneous communications at a lower rate (i.e., only one stream per link). Then we extend it toward the general SM-MIMO system and describe the full version of MIMOMAN.

### 2.1 Preliminaries

The MIMO system can be thought of as a linear system where the input and output are vectors as shown in Figure 1. In the system, signals, channel coefficients, and antenna weights are all represented as complex numbers. Assuming $N$ antennas at both the transmitter and receiver, the MIMO channel between them is represented with an $N$x$N$ matrix of channel coefficients $\mathbf{H}$ where the $h_{ij}$ element represents the individual channel gain between the $i^{th}$ transmitter antenna and $j^{th}$ receiver antenna as shown in Figure 3. In rich scattering environments such as indoor or urban outdoor, $\mathbf{H}$ will be full-rank and can be characterized as a random matrix. The input $\mathbf{x}$ is the transmitted symbol vector and the output $\mathbf{y}$ is a received signal vector. The input $\mathbf{x}$ is linearly transformed by the channel $\mathbf{H}$ and appended with noise $\mathbf{n}$ resulting in the output $\mathbf{y}$. Given $\mathbf{H}$ and disregarding $\mathbf{n}$, the transmitted symbol vector $\mathbf{x}$ can be retrieved from the received signal vector $\mathbf{y}$ by $\mathbf{x} = \mathbf{H}^{-1}\mathbf{y}$, which is one of the simplest SM-MIMO decoders called zero-forcing decoder. A channel estimation procedure

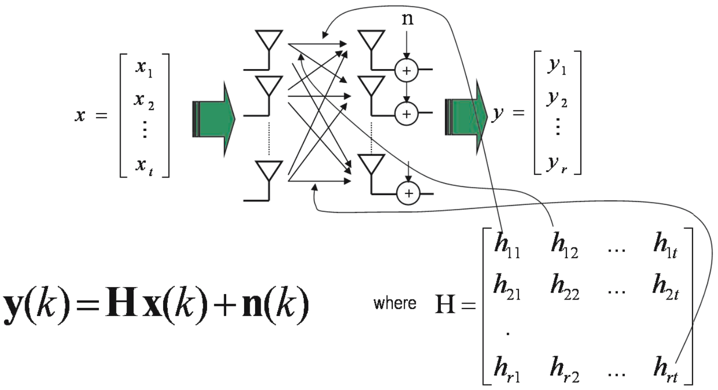

**Fig. 1.** MIMO channel

precedes the real data exchange to get the channel $\mathbf{H}$. For better performance, additional signal processing operations can be applied to the transmitted and received signal vector, which can be represented as $\mathbf{y} = \mathbf{VHUx}$ where $\mathbf{U}$ and $\mathbf{V}$ are transmitter and receiver signal processing operations respectively. $\mathbf{U}$ and $\mathbf{V}$ are sometimes called transmitter/receiver beamforming. Through out this paper, we use uppercase and lowercase boldface letters to denote matrices and vectors, respectively, and superscripts T and H to denote the transpose operation and Hermitian operation, respectively. In our MAC designs, we maintain two logical channels, Control Channel and Data Channel, among which the total available bandwidth is divided. This division may be either frequency or code based. Only unicast DATA frames are sent over Data Channel. All other frames, RTS, CTS, ACK, and broadcast DATA frames, are sent over Control Channel. We assume the transceiver installed on each node is capable of listening to both channels concurrently but able to transmit over only one channel at a time. We assume flat fading meaning the two channels undergo the same channel characteristics. Our MAC protocols are based on IEEE 802.11 DCF MAC. Unless otherwise specified, our MAC protocols obey IEEE 802.11 DCF rules such as the exponential backoff.

### 2.2 bMIMOMAN: A Restricted Version of MIMOMAN

Figure 3 illustrates the abstract model of beamforming MIMO that bMIMOMAN is targeting. This type of MIMO transmits only one symbol at a time forming only one stream between a transmitter-receiver pair. By a stream we mean a time series of signals. At the transmitter side, each antenna transmits the same symbol or signal after applying its own weight to the signal (e.g., in the figure Antenna 1 transmits $s(t)w_{T1}$). At the receiver, received signals from all antennas are individually weighted and summed allowing the output $r(t) = s(t)\ \mathbf{w_T^H H w_R}$ where $\mathbf{w_T}$ is the weight vector $(w_{T1}\ w_{T2}\ w_{T3}\ w_{T4})^T$ of the transmitter, $\mathbf{H}$ is the MIMO channel matrix between the two nodes, and $\mathbf{w_R}$ is the weight vector

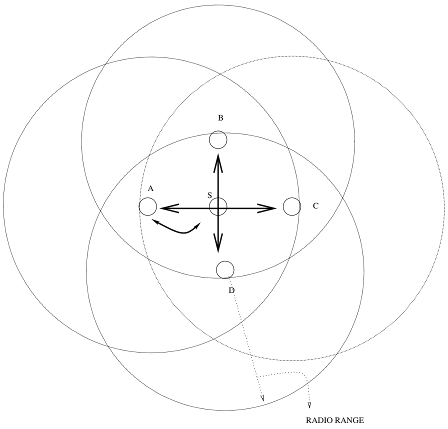

**Fig. 2.** Network Topology Example

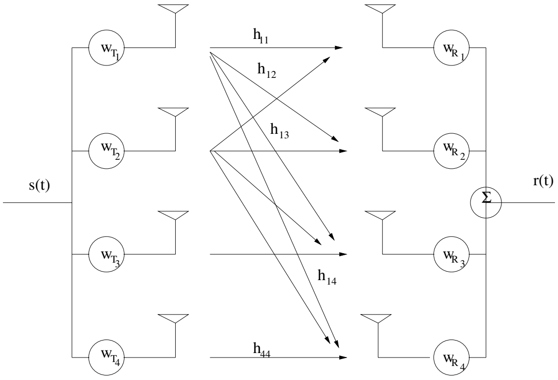

**Fig. 3.** Beamforming MIMO schematic with 4 antennas at both ends

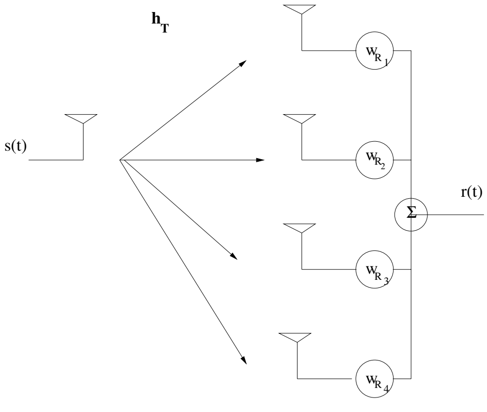

**Fig. 4.** Effective channel $\mathbf{h_T} = \mathbf{w_T^H H}$

of the receiver. The MIMO channel can be thought of as SIMO channel as shown in Figure 2.1. The effective channel then is $\mathbf{h_T} = \mathbf{w_T^H H}$. We assume that coefficients of the effective channel can be estimated using standard channel estimations methods. RTS and CTS MAC control frames shall carry training symbols for that purpose.

To allow simultaneous multiple transmissions, both ends beamform, i.e., adjust antenna weights, as follows:

1. Transmitter selects $\mathbf{w_T}$ such that it does not affect any ongoing communications.
2. Receiver selects $\mathbf{w_R}$ such that it receives only signal of interest and is not interfered by any other ongoing communications.

Let us consider a small network shown in Figure 2. Say at some point Node B wants to transmit a packet to Node D while Node C is sending a packet to A. If D can null the signal being transmitted from A to C and B transmits a signal which is nulled from A and C's perspective, we are enabling the two simultaneous transmissions. A node can null a signal easily if it knows the weight vector being used to transmit the signal. For example, D can null the signal from C by setting $\mathbf{w_D}$ such that $\mathbf{w_C^H H_{CD} w_D} = 0$ where $\mathbf{H_{CD}}$ is the channel matrix between C and D. Also, a node can generate a signal that is nulled from the perspective of a certain receiver if it knows the weight vector of the receiver. For example, by adjusting $\mathbf{w_D}$ such that $\mathbf{w_D^H H_{DA} w_A} = 0$, D can transmit a signal that means nothing to A. In our scenario, to accomplish the two simultaneous communications, A should know $\mathbf{w_B}$ and $\mathbf{w_D}$ where $\mathbf{w_B}$ and $\mathbf{w_D}$ are the weight vectors of B and D respectively and D should know $\mathbf{w_A}$ and $\mathbf{w_C}$ where $\mathbf{w_A}$ and $\mathbf{w_C}$ are the weight vectors of A and C respectively. This exchange of weight vectors is enabled by the procedure described subsequently.

Consider the topology shown in Figure 2 again. Assume at the beginning all the nodes are silent, i.e., there is no on-going communication. A node which wants to transmit data to another node, say Node A, transmits a RTS using the default weight vector, $[\mathbf{1\ 1\ 1\ 1}]/\sqrt{\mathbf{4}}$ in our 4-antenna example, or a random vector. The vector is normalized to have equal signal power regardless of the number of antennas. Note that different signal power results in different link performance. The weight vector used to transmit the RTS will be reused to transmit the following data packet and to receive the corresponding CTS. Once the designated receiver of the RTS, say Node C, receives the RTS, it responds with a CTS packet using the current weight vector. The weight vector used for transmitting CTS will be used to receive following data packet. The receiver estimates the SIMO channel vector $\mathbf{h_{AC}} = \mathbf{w_A^H H_{AC}}$. Since there is no on-going communication, Node C can switch its weight vector to $\mathbf{w_C} = \mathbf{h_{AC}^T}$ which maximizes the combined channel and array gain before it transmits CTS. When a node other than the designated receiver receives RTS, say Node D in our example, it estimates the effective channel $\mathbf{h}$ and adjusts the weight vector such that the signal from the sender of RTS is nullified (i.e., $\mathbf{h_{AD} w_D} = 0$) for the duration of time specified in the RTS duration field. When a node other than the sender of the RTS receives the CTS, say Node S, it estimates the effective channel and stores the weight vector for the duration specified in the CTS duration filed. After the RTS/CTS handshaking Node A sends and C receives a data frame using $\mathbf{w_A}$ and $\mathbf{w_C}$ respectively. For the physical carrier sensing, a node listens to the Control Channel. If the Control Channel is free, it assume the wireless channel is free as in 802.11 case.

Now let us say B wants to initiate a data transmission toward D. Since it should ensure that C's signal reception is not disturbed, it picks a $\mathbf{w_B}$ such that $\mathbf{w_C^H H_{CB} w_B} = 0$ for a RTS transmission. The RTS itself does not interfere with data transmission but for the estimation purpose the beamformed version of the RTS has to be transmitted. Note that B already obtained $\mathbf{w_C^H H_{CB}}$ when it overheard C's CTS. B's counterpart, Node D, has to pick its weight vector such that the signal from A is nullified. Otherwise, D's decoding of the signal from B will be hindered by the interference from A. In fact, D already has done it when it overheard A's RTS so it either can use its current weight vector or select a new $\mathbf{w_D}$ such that the effective channel gain from B is maximized while the signal from A is nullified. This problem can be formulated as an optimization problem and using null-space projection it can be reduced to an eigenvalue problem in our case. The detailed algorithm is to be described in the next section. Note that any additional new transmission is only possible if both the sender and receiver have enough degrees of freedom. A node with $N$ antennas can null out at most $N - 1$ stations in rich scattering environments. $N$ is also known as the Degree of Freedom (DOF). Every time a node nulls out another node, it consumes one DOF. For example, a node with 4 antennas can null out the maximum of 3 other transmitters while transmitting its own stream.

A node should not start a new transmission if it cannot finish its transmission in the communication period (time to exchange RTS, CTS, DATA and ACK frames) of any ongoing communication. The reason is that during the course of communication nodes are unable to track neighbors' activities. So if a new transaction has commenced during their communication, there is high chance of either disturbing the new transmission or loosing the opportunity to start another transaction. Imagine a situation where A and B are in the range of D but they are hidden terminals to each other and A just finished its communication session and D is receiving B's signal. A sees a clear channel but it doesn't mean there is no activity. A would have known D's activity if it was not engaged in its communication beforehand. In ad hoc networks with conventional radios and MACs, this kind of situation does not happen.

The new restriction can be harsh for some nodes. If all the packets are the same size, then there cannot be any simultaneous transmissions. We get around this problem using the common packet aggregation technique. A node reserves the channel for a long period and send out multiple packets back-to-back. In 802.11 terms, we make PHY frames carry multiple MAC frames. In this way the session duration is made variable regardless of traffic so that several simultaneous sessions can be stack up. The packet aggregation technique is known to enhance channel utilization since it amortizes the fixed RTS/CTS overhead among multiple MAC frames.

When a node receives a RTS or CTS, the node stores all the information, the effective channel coefficient and the duration of the session, delivered by it. This is necessary because a node may not have enough degree of freedom to null out interfering signal. When a node receives RTS or CTS and it is out of DOF, it sets NAV to the closest finish time of on-going session. When NAV expires we recalculate the weightvector.

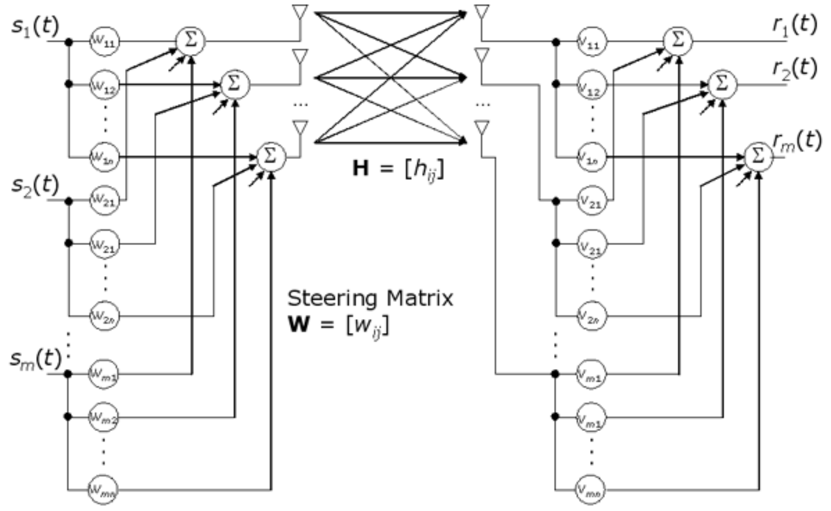

**Fig. 5.** MIMOMAN link model

## 2.3 MIMOMAN

In this section, we generalize bMIMOMAN toward spatial multiplexing MIMO and develop the full version of MIMOMAN. Figure 5 illustrates the SM-MIMO link model. As mentioned previously, SM-MIMO can transmit multiple signal/streams concurrently. At the sender, each stream/signal is applied its own weightvector and then all of them are summed and transmitted out of $N$ antennas. At the receiver, multiple streams are generated by applying different weighvectors to the received signal vector and those are fed to MIMO decoder. For sending and receiving, each node maintains a weight matrix (or steering matrix) which is a collection of vectors since we need one weightvector for each stream. The relationship between the input signal vector at the transmitter and output signal vector at the receiver can be represented as $\mathbf{r}(t) = \mathbf{s}(t)\ \mathbf{W^H H V}$ where $\mathbf{W}$, $\mathbf{H}$, and $\mathbf{V}$ are the weight matrix of the transmitter, the channel matrix, and the weight matrix of the receiver respectively. In fact, multiple streams in a communication link can be thought of as multiple senders and receivers each transmitting and receiving one stream sharing a channel. Following this track, bMIMOMAN can be naturally extended to spatial multiplexing MIMO. We use the story plot similar to the one used in the previous section for easier understanding by comparison. We assume that the total transmission power is constrained by the number of antennas.

At the beginning, Node A having data designated to another node, say Node C, transmits a RTS frame. In SM-MIMO networks with heterogeneous antenna settings, there is an issue in sending and receiving frames regarding the number of antennas and streams. If a node with 4 antennas sends a frame with 4 streams then only nodes with more than four antennas can decode the frame. Since the RTS sender does not know how many antennas the neighbor nodes including designated and non-designated receivers have or what channel condition they are experiencing, every RTS frame is sent using one stream. In the RTS frame, it is indicated that how many antennas the sender has and how many streams can be employed when sending following DATA. The number of available streams depends on the channel condition. As noted earlier, A node with $N$ antennas can suppress up to $N$ - 1 streams, i.e., it can transmit without interfering nodes receiving total $N$ - 1 streams. How to set this value will be elaborated shortly.

For a receiver to decode multiple streams, it should aware of the effective channel for each stream. In the beamforming MIMO case, since each stream generates one RTS, the receiver can estimate the effective channels of multiple streams one by one. But in this case one RTS is for multiple streams thus RTS should be designed such that the effective channel estimation can performed for each stream. It is indicated that a block of training symbols is in the RTS such that the effective channel can be estimated. To do the channel estimation for multiple streams, the block is replicated as many time as the number of streams. Each block serves for each streams. The weightvector associated to a specific stream is applied when sending out the block corresponding to the stream.

This way, the neighbors of Node A learn $\mathbf{W}_{\mathbf{A}}^{\mathbf{H}}\mathbf{H}$. In response to the RTS, Node C, the designated receiver, transmits a CTS frame towards Node A. Similarly, its neighbors learn their $\mathbf{W}_{\mathbf{B}}^{\mathbf{H}}\mathbf{H}$'s. We set $\mathbf{W}_{\mathbf{B}}$ as the right singular vectors of $\mathbf{W}_{\mathbf{A}}^{\mathbf{H}}\mathbf{H}$, i.e., $\mathbf{W}_{\mathbf{B}} = \mathbf{V}$ where $\mathbf{W}_{\mathbf{A}}^{\mathbf{H}}\mathbf{H} = \mathbf{U}^{\mathbf{H}}\mathbf{D}\mathbf{V}$ is a singular vector decomposition. This is to maximize SINR. For the same reason as the RTS case, a CTS should be sent out using one stream and carry blocks of training symbols. In the CTS frame, it is indicated that how many antennas the sender of the frame has and how many streams can be accepted for the following DATA communication. The number of acceptable streams depends on the channel condition and should be equal to or less than the number of available streams of the corresponding RTS sender. Once Node A receives the CTS, Node A starts transmission of DATA using the number of streams indicated in the CTS.

Now let's say Node B has data to send out. When transmitting frames, B should not interfere C's reception of data. To that end, B has to control the number of streams and set the weight matrix, i.e., beamform, appropriately. As indicated earlier, the total number of streams to be suppressed and to be transmitted at the same time is the same as the number of antennas installed on the node.

We can solve the stream control and beamforming problem jointly for the general case at Node S as follows. Let

$k$ = the number of receiving neighbors, Node 1 to $k$, not to interfere,
$\mathbf{H_{iS}}$ = channel between Node i and S,
$\mathbf{S_i}$ = steering matrix of Node i,
$\mathbf{Z_{iS}} = \mathbf{H_{iS}^H S_i S_i^H H_{iS}}$, and
$\mathbf{Q} = \sum_{i=1}^{k} \mathbf{Z}_{iS} = \mathbf{PDP^T}$ which is an eigenvalue decomposition.

We first find the largest m such that $\lambda_{n-m+1} \leq \alpha$, 0 in our current design, where $\lambda_p$ is $\mathbf{D}(p, p)$ ($p^{th}$ largest eigenvalue of Q) and $n$ is the number of antennas of Node S. And we set S's steering matrix $\mathbf{W_S} = [\mathbf{P}_n \ldots \mathbf{P}_{n-m+1}\ \mathbf{z} \ldots \mathbf{z}]$ where $\mathbf{P}_i$ is $i^{th}$ column of $\mathbf{P}$ and $\mathbf{z}$ is zero column vector. Last (n - m) columns of $\mathbf{W_S}$ are zero columns. If there is no such $\lambda$, the transmission should not commence. From their CTSs transmission neighboring receivers are identified and corresponding $\mathbf{S_i^H H_i S}$ is estimated. Referring to the scenario depicted in Figure 2, once Node S starts a new transmission, Node 1, 2, 3, and 4 will undergo the interference with energy tr($\mathbf{W_S^H H_{1S}^H W_1 W_1^H H_{1S} W_S}$), tr($\mathbf{W_S^H H_{2S}^H W_2 W_2^H H_{2S} W_S}$), tr($\mathbf{W_S^H H_{3S}^H W_3 W_3^H H_{3S} W_S}$), and tr($\mathbf{W_S^H H_{4S}^H W_4 W_4^H H_{4S} W_S}$) respectively where tr() denotes the trace operation. What we do is choose such $\mathbf{W_S}$ that those interferences are nulled.

The beamforming problem at the receiver can be solved similarly. We maximize channel gain from the transmitter while nullify other known interfering signals. Let there be Node T and R, the transmitter and receiver, as well as $k$ interferers, Node 1 to $k$. We define

$\mathbf{H_{iR}}$ = channel between Node i and R,
$\mathbf{S_i}$ = steering matrix of Node i,
$\mathbf{Z_{iR}} = \mathbf{H_{iR}^H S_i S_i^H H_{iR}}$, and
$\mathbf{Q} = \sum_{i=1}^{k} \mathbf{Z}_{iR} = \mathbf{PDP}^T$.

We find the largest m such that $\lambda_{n-m+1} = \alpha$ (= 0 in our current design) where $\lambda_p$ is $\mathbf{D}(p, p)$ ($p^{th}$ largest eigenvalue of Q). If there is no such $\lambda$, it means that a node cannot suppress known interferers thus the reception should not commence. Otherwise m becomes the number of available streams at the receiver. And let

$\mathbf{U} = [\mathbf{P}_n \ldots \mathbf{P_{n-m+1}}]$,
$\mathbf{N} = \mathbf{UU}^H$, and
$\mathbf{M} = \mathbf{NZ_{RT}N} = \mathbf{XAX}^T$.

Set R's steering matrix $\mathbf{W_R} = [\mathbf{X_n} \ldots \mathbf{X_{(n-m+1)}}\ \mathbf{z} \ldots \mathbf{z}]$ where $\mathbf{X_i}$ is $i^{th}$ column of $\mathbf{X}$. What we are doing here is optimizing the combined channel and antenna array gain between the the transmitter while nullifying known interferes. We formulate the problem as an optimization problem and using null-space projection it is reduced to an eigenvalue problem.

The main advantage of MIMOMAN compared to legacy 802.11 style MACs comes from the fact that it gives more *power* to the nodes with larger number of antennas. From a node with larger number of antennas point of view, the wireless channel captured by another node with fewer number of antennas is underutilized. Once the underutilization is detected, MIMOMAN allows high power nodes to kick in. By overhearing RTSs and CTSs, a node can identify the underutilization of the channel as described above.

The sender and receiver negotiate the number of streams to be used for the data transmission. This means that the data rate and thus transmission time of a frame will vary. This causes several problems including setting the *duration* field in the RTS. We get around the problem again with the packet aggregation technique described in the previous section.

When preparing a RTS frame, a sender collects as many packets as possible from the application layer and calculates the time to transmit all the packets at the highest possible rate. The highest possible rate depends on the channel condition. It is (base rate) * (number of antennas - number of known receiving neighbors). If there is no interferer, the sender sets the duration field as the smaller value of the channel coherence time which is predefined and the expected transmission time. The channel coherence time is expected time during which the channel doesn't change. When node are moving with the speed of 10 m/s, it is about 10ms according to [12]. If there is any known on-going communication, the sender sets the duration field as the earliest termination time of any on-going communication. But a sender should be able to send at least one packet so if the earliest termination time of any on-going communications is less than the transmission time of the first packet at the base rate then, the sender should not initiate any data transmission procedure.

On the reception of CTS, the data rate is known to the sender since it is indicated in the CTS how many streams can be employed transmitting data. The sender creates an aggregated DATA frame by packing as many packets that can be transmitted in the duration specified in the CTS at the rate specified in the CTS.

## 3 Performance Evaluation

In this section we describe our simulation setup and present the results characterizing the performance of MIMOMAN.

We implemented MIMOMAN in Qualnet [9]. Data structures holding antenna/stream weights and the channel information are added and the gain due to the MIMO channel **H** which is instantiated whenever needed and antenna weights is calculated on the fly and applied to the computation of the Signal-to-Noise ratio (SNR) for each packet. We assume a quasi-static Rayleigh fading environment [11]. The channel coefficient for each transmit-receive antenna pair is an i.i.d. complex Gaussian random variable with zero mean unit variance and the channel is invariant during a complete session including RTS, CTS, and DATA frames. We assume that the channel estimation can be done with no error. Beamforming algorithms in the simulator are implemented using LAPACK [5]. We use the SNR threshold based reception model and the threshold value of 10dB which is the usual number for single antenna based network simulations. In fact, the more antennas the less the bit error rate is. That is, the bit error ratio of the 4x4 sys-

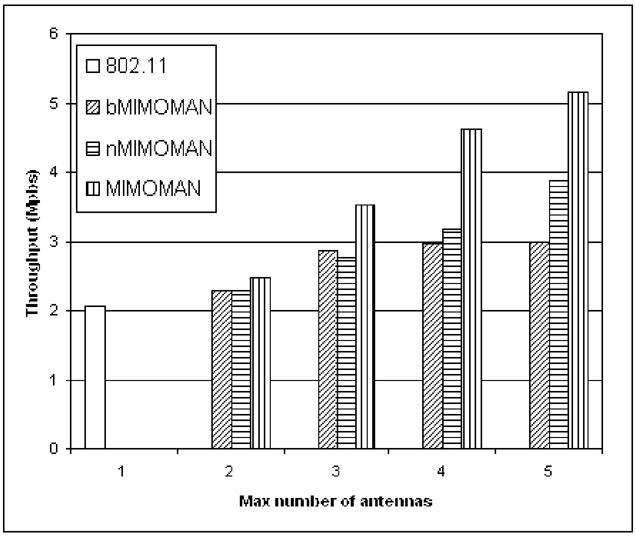

**Fig. 6.** Comparison of throughput of MIMOMAN protocols (20 node randomly deployed on 700x100$m^2$ field)

tem is less than 2x2 or 1x1 system for the same SNR. We use the same threshold regardless of the number of antennas/streams employed, which is a rather conservative approach. More realistic reception error model is BER based which we plan to use for future work. It requires two step procedure: First, generate a BER table by performing separate link-level simulation. Then integrate the BER table into our simulation environment. We use the default values as Qualnet provides for the configurable parameters (e.g., 15dBm transmission power) unless otherwise specified. The radio range is about 250m.

We compare four protocols: 802.11, bMIMOMAN, nMIMOMAN, and MIMOMAN. nMIMOMAN is another restricted version of MIMOMAN. Contrary to bMIMOMAN, it does not allow simultaneous communicating node pairs but a node can use multiples streams to transmit data. Thus beamforming in nMIMOMAN only can increase SNR. And like MIMOMAN, stream number negotiation and packet aggregation are performed. Out of total 2Mbps link bandwidth 1.6Mbps is allocated to Data Channel. 802.11 uses only one channel of 2Mbbs. We set the channel coherence time to 10ms.

We consider a saturated network scenario with 20 static nodes randomly distributed over the 700x100$m^2$ field. Each node varies in the number of antennas installed. Each node is assigned a random number between 1 and the maximum value of antennas. In the 802.11 case the maximum number can only be 1. Every node generates constant bit rate (CBR) traffic of 1000 packets/sec and 1KB/packet. Not to be influence by higher layer protocols static routes are used and each node sends packets only to one of its 1-hop neighbors. We measure

*Throughput* which is defined as the total number of data bits received by all the nodes divided by the simulation time. Figure 6 illustrates the performance of the protocols as a function of the maximum number of antennas. The numbers are averaged over 10 independent simulation runs. Typical hardware limitations might not allow the manufacture of a laptop or a mobile device with more than 5 antennas, hence we limit our simulations to the max 5-antenna case. The most notable result demonstrated in the figure is that MIMOMAN's performance scales well with the maximum number of antennas compared to others. MIMOMAN shows about 35% throughput enhancement per antenna over 802.11. In the max 5-antenna case, the improvement is around 150% over 802.11, 75% over bMIMOMAN, and 35% over nMIMOMAN. The reason why bMIMOMAN cannot keep up with MIMOMAN is that for each initiation of a communication session, the network incurs overhead due to RTS/CTS handshaking and collision of RTSs. Since bMIMOMAN allows only one stream per communicating node pair, to saturate the wireless channel, i.e., nodes completely consume their DOFs, in a certain period of time bMIMOMAN should initiate several communications in the time frame. Thus the overhead can be quite high and the saturation may not be possible in some cases. Whereas MIMOMAN saturates the channel with fewer number of communications since multiples streams per communication are permitted. bMIMOMAN exhibits only about 45% improvement over 802.11 even in the max 5-antenna case. Since only one communication is permitted in a collision domain, the channel has to be underutilized unless nodes with the highest number of antennas capture the channel always which is prevented by contention scheme used in 802.11 from which nMIMOMAN is driven. This guarantees some level fairness, that situation is prevented. Whereas in MIMOMAN case, if a node detects underutilization of the channel it will kick in to take advantage of it, which gives full exploitation the channel thereby higher throughput than nMIMOMAN. Note that 802.11's achieved throughput higher than the channel bandwidth is due to enough spatial separation between nodes. Intuitively, the throughout should increase with the number of antennas since the nodes will have more degrees of freedom to take advantage of the underutilized channel. However the increase is not $N$-fold, where $N$ is the maximum number of antennas. MIMOMAN does not achieve the expected maximum factor improvement of throughput for several reasons such as channel division, MAC control frame overheads, packet aggregation overhead, and aforementioned session initiation overhead.

## 4 Conclusion

In this paper, we presented MIMOMAN, a MIMO Mac protocol for Ad hoc Networks. MIMOMAN provides a methodology with which nodes can identify interferers and acquire channel information to implement transmit and receive antenna beamforming that achieves spatial multiplexing while at the same time nulling of co-existing, potentially interfering transmitter/receiver pairs. Our simulation results confirmed the advantages of MIMOMAN.

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