

Antenna Selection Diversity based MAC Protocol for MIMO Ad hoc wireless Networks

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Abstract—In this paper, we propose a novel asynchronous Media Access Control (MAC) protocol, Opportunistic MAC (OMAC), for Multiple Input Multiple Output (MIMO) ad-hoc networks. The proposed solution is based on closed loop minimal feedback antenna selection diversity scheme and optimum receive combining. The use of antenna selection diversity contributes to a reduction in the feedback information and the effective interference produced. To utilize the spatial degrees of freedom offered by MIMO, we propose the use of a novel rank based metric to obtain interference information as well as to enable multiple simultaneous transmissions and to make MAC decisions. The rank of the interference matrix, (R_I) is used as a metric. We present the performance of the proposed solution from the throughput perspective for a single hop ad-hoc wireless network. Through analysis and simulation, we found that the proposed protocol significantly outperforms 802.11 MIMO and it obtained as high spatial degree of freedom utilization as 85%.

I. INTRODUCTION

Ad-hoc wireless networking has been an important type of network to provide communication in unplanned infrastructure-based or infrastructure-less communication scenarios. It is well known that MIMO techniques can highly increase the capacity of the point-to-point as well as multi-user communication systems. Consequently, there is considerable interest in utilizing MIMO techniques in an ad-hoc wireless network environment. Previous theoretical work on capacity of ad-hoc networks has mainly concentrated on the area of throughput scaling as the network size grows asymptotically. Most notable work is by Gupta and Kumar [1]. In their formulation, the MIMO physical layer was not considered.

In [2], capacity scaling for MIMO is considered for various diversity techniques and theoretical performance limits of various MIMO options are given. Effective throughput of a poisson distributed network is calculated by finding effective outage probabilities of various diversity schemes. As conjectured in [2], [3], diversity achieving schemes have better performance in low SNR ad-hoc network.

In [4], [5], [6] various MIMO based MAC protocols are proposed. In [4], [5], [6], beamforming methods are used to nullify the interfering signal. These methods involve complete channel feedback from the receiver side, as well as keeping track of channel knowledge from the interferers at the intended receiver. Such beamforming information exchange not only incurs high overhead in terms of resource consumption, but also limits network scalability. Antenna selection based spatial diversity technique is an important diversity techniques

in MIMO and the following attractive features for ad hoc networks:

- Antenna selection based spatial diversity requires feedback from the receiver about the best antenna to transmit on. This can be done with minimal feedback. Furthermore, the selection of the best antenna is not usually changing fast in a limited mobility environment. Hence the feedback is also potentially robust in time varying environments.
- The diversity gain obtained by antenna selection diversity is the same as those obtained using space-time codes. However, the additional power gain facilitates lower interference to other transmissions. Furthermore, the use of a single antenna restricts the interference to lie in one spatial dimension thereby enabling interference suppression by spatial means, *i.e.* optimum combining. In contrast to cellular systems, the antenna selection approach enhances the user's SNR without increasing the interference to the other users.
- The use of only one spatial degree of freedom by antenna selection enables multiple simultaneous transmission and also benefits from multiuser diversity making the overall throughput higher than a single point to point link.
- The omnidirectional transmission from the selected antenna avoids the problem that is aggravated by directional/beamforming based precoding transmission strategies, e.g. hidden terminals.

Motivated by the above considerations, we develop a MIMO MAC protocol based on antenna selection diversity. An important issue in this context is identifying the number of ongoing transmissions without significant overhead. One of the main contributions of this paper is the new physical layer metric, $Rank(R_I)$, that is used as an estimate of the number of transmitting neighbors.

The rest of this paper is organized as follows. In Section II-A, we describe the physical layer optimum combining technique used in our protocol. In Section II-C, we describe our protocol, a controlled method to increase the number of simultaneous transmission as well as maximize the packet transmission success. In Section III, we give saturation throughput analysis of the proposed protocol for a single-hop ad hoc network. Section IV compares the analytical results with the simulated environment and Section V concludes the paper.

II. MIMO MAC DESIGN

We first describe the link level model and MIMO-adapted carrier sensing which will be followed by our extension of the standard 802.11 DCF protocol to incorporate the capabilities of MIMO. We use MIMO-adapted carrier sensing in order to allow simultaneous transmissions asynchronously.

A. Link Level Model

Consider a typical transmission between a receiver r and a transmitter t with M antennas each. We assume that the transmission between t and r is under the presence of N_I co-channel interferers. We consider the case when the number of interferers are less than the number of antennas i.e. $N_I < M$ because the OMAC protocol ensures that the number of simultaneous transmissions does not exceed M . The interferers also use the same transmission scheme as that employed by transmitter t to transmit to their respective receivers. The channel coefficient between transmitter j and receiver i is given by H_{ij} , where $H_{ij} \in \mathcal{C}^{M \times M}$ and have independent and identically distributed (i.i.d.), zero-mean, complex Gaussian elements $\sim \mathcal{CN}(0, 1)$. The received signal at the receiver r , \mathbf{Y}_r is given by,

$$\mathbf{Y}_r = \mathbf{H}_{rt}\mathbf{x}_t + \sum_{i=1}^{N_I} \mathbf{H}_{ri}\mathbf{x}_i + \mathbf{N}_r, \quad (1)$$

where $\mathbf{N}_r \sim \mathcal{CN}(0, N_0)$ is the thermal noise at the receiver, and \mathbf{x}_i are the transmitted data vectors. We use antenna selection diversity at the transmitter, so the transmitter transmits with one antenna. Assuming that antenna a_i was chosen by transmitter i , we have the received signal given by

$$\mathbf{Y}_r = \mathbf{h}_{a_t,rt} s_t + \sum_{i=1}^{N_I} \mathbf{h}_{a_i,ri} s_i + \mathbf{N}_r.$$

where the column corresponding to the antenna chosen by transmitter i for transmission is denoted by $\mathbf{h}_{a_i,ri}$ and the transmitted symbol is s_i with power p_i . Note that only a_t corresponds to the column of \mathbf{H}_{rt} with the largest norm. At the receiver, optimum combining is performed.

Assuming a block fading model, the interference covariance \tilde{R}_I is given as,

$$\begin{aligned} \tilde{R}_I &= \mathbf{E} \left(\sum_{i=1}^{N_I} \mathbf{h}_{a_i,ri} s_i + \mathbf{N}_r \right) \left(\sum_{i=1}^{N_I} \mathbf{h}_{a_i,ri} s_i + \mathbf{N}_r \right)^H \quad (2) \\ &= \sum_{i=1}^{N_I} p_i \mathbf{h}_{a_i,ri} \mathbf{h}_{a_i,ri}^H + N_0 \mathbf{I} \end{aligned}$$

At the intended receiver, the received signal, is pre-multiplied with the linear combining weights given by, $\tilde{R}_I^{-1} \mathbf{h}_{a_t,rt}$. The SNR at the output of the optimum combiner is then given by, $\gamma = p_t \mathbf{h}_{a_t,rt}^H \tilde{R}_I^{-1} \mathbf{h}_{a_t,rt}$. For most common modulations, the general form of probability of symbol error, when the interference is Gaussian is given as,

$$P_b(E) = \int_{-\infty}^{\infty} Q(g\sqrt{\gamma}) p(\gamma) d\gamma, \quad (3)$$

TABLE I
SNR $\frac{P_t}{N_0} = 20$ dB, $M=4$

$\frac{P_t}{P_i}$	$N_I = 1$	$N_I = 2$	$N_I = 3$
-6 dB	0	10^{-6}	3.7×10^{-5}
-4 dB	0	10^{-7}	1.3×10^{-5}
-2 dB	0	0	3×10^{-6}
0 dB	0	0	10^{-7}

where γ is the SINR for a scheme, and g is a constant depending the modulation scheme used. Table I specifies typical values for P_b for BPSK modulation.

B. 802.11 DCF Protocol

The traditional 802.11 DCF protocol is based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), with physical and virtual carrier sensing carried out at the physical and the MAC layer, respectively. There are two access mechanisms for packet transmission in 802.11 DCF. The default is two-way handshaking, known as the basic access method. In basic access method an acknowledgment (ACK) packet is sent by the receiver to confirm the reception of the data packet. The other method is to use four way RTS/CTS/DATA/ACK mechanism to reserve the channel if the data packet length is greater than threshold. The node proceeds with transmission, either data or an RTS packet, if the medium is sensed idle for more than Distributed Inter Frame Space (DIFS). If the medium is busy, the node defers until a DIFS is detected and then generates a random back-off period before transmitting. The back-off timer counter is decreased as long as the channel is sensed idle, frozen when the channel is sensed busy, and resumed when the channel is sensed idle again for more than a DIFS. Each node maintains a counter, whose initial value is set to a random integer uniformly distributed in $[0, W_0 - 1]$, where $[0, W_0 - 1]$ is referred to as the initial backoff window. The counter is decremented at each time slot till it reaches zero, at which a data transmission is attempted. If a collision occurs, the backoff window is doubled. If the channel is not idle for a period of DIFS, the IEEE 802.11 DCF stays away from transmission.

C. OMAC protocol

We propose Opportunistic MAC Protocol (OMAC) that exploits the opportunities of simultaneous transmissions by using a novel rank-based physical layer metric in order to maximize the utilization of the degrees of freedom in MIMO ad hoc wireless networks. The basic CSMA/CA is at the heart of the proposed OMAC protocol, but uses MIMO-adapted carrier sensing designed specifically for MIMO systems. As mentioned above, the most important issue in the design of MIMO MAC protocols is the estimation of the number of transmitting users. Existing protocols utilize information gathered from the MAC headers and the overheard transmissions. However, all these strategies lead to high protocol overhead and therefore, the MAC protocols designed for MIMO systems face the critical question of scalability. In most of existing

protocols, information necessary for MAC protocols cannot be acquired when a node is transmitting. We chose a novel alternative, rank of the correlation Matrix, $\text{Rank}(R_I)$, for estimating the number of active transmitters on the channel. The $\text{Rank}(R_I)$ is then used for MIMO-adapted carrier sensing to help the MAC design. The $\text{Rank}(R_I)$ is calculated as,

$$R_I = \sum_{i=1}^{N_I} p_i \mathbf{h}_{a_i, r_i} \mathbf{h}_{a_i, r_i}^H \quad (4)$$

It is an indicator of the number of transmitters or number of transmission elements. From Equation 2 and 4, notice that R_I is the interference correlation matrix \hat{R}_I without white noise. Any node can calculate the R_I using a window of signal samples received. In this work, we assume that the $\text{Rank}(R_I)$ can be accurately estimated.

When a transmitter node, t , has packets to be transmitted to a receiver node r , t senses the channel for activity and calculated R_I using time average correlation matrix of ongoing transmissions. In OMAC, the sender uses the $\text{Rank}(R_I)$ as a measure of the channel idleness. $\text{Rank}(R_I)$ can be viewed as a metric for the extension of physical carrier sensing to the MIMO networks. That is, once the estimation of $\text{Rank}(I)$ is carried out, the following rules are used for the operation of the OMAC protocol:

- 1) $\text{Rank}(R_I)$ represents the number of users or the number of antenna elements in use within the broadcast region. Thus, if $\text{Rank}(R_I)$ is zero, then the channel is estimated to be completely idle and the sender node can proceed with the transmission only if the channel remains the same or follows rule (2) for a period of DIFS duration.
- 2) $\text{Rank}(R_I) = X$ where $0 < X < M$ and X is the number of effective transmitters or transmitting elements present in the neighborhood where the maximum number of antenna elements per node is M . In this case, the sender can still proceed with transmission if the channel state follows rule (1) or (2) for a period of DIFS duration.
- 3) $\text{Rank}(R_I) = M$ represents full rank of the R_I vector which, in OMAC protocol, is considered as the busy state of the channel and the sender must now enter to the binary exponential back-off stage.
- 4) During the back-off stage if the channel state changes from $\text{Rank}(R_I) < M$ to $\text{Rank}(R_I) = M$, then the backoff counter is frozen, similar to the CSMA/CA protocol, until the $\text{Rank}(R_I)$ becomes less than M . Once the $\text{Rank}(R_I) < M$ is satisfied, then the backoff counter decrementing process is restarted. When the backoff counter reaches zero, then the sender begins its transmission based on the selected antennas elements at that time.
- 5) At the receiver, if the condition $\text{Rank}(R_I) < M$ is satisfied, based on the $\text{Rank}(R_I)$ estimation carried out before RTS reception, a CTS is transmitted.

When node r transmits the CTS, an important decision to be made is the right antenna element to be used for



Fig. 1. Timing diagram of the Bi-directional model.

the DATA/ACK transmission. We define a new parameter for the receiver antenna selection named Transmit Element State Information (TESI) which is defined for the i^{th} transmit antenna element as,

$$TESI_i = \sum_{j=1}^M |h_{rt}^{ij}|^2, \quad (5)$$

where h_{rt}^{ij} denotes the coefficient of fading and path loss for the spatial channel between i^{th} transmit antenna element and the j^{th} receive antenna element. Here we order the antenna elements at the receiver r , in non-increasing order of TESI and return the best antenna element while transmitting the DATA/ACK packets.

We transmit RTC/CTS using Space Time Block Codes (STBC) while DATA and ACK are transmitted using antenna selection diversity. Transmitting RTS using STBC has two important benefits. It can be used for channel estimation from all the transmitter antennas and it gives robustness to the RTS packet. While transmitting RTS, the transmitter does not have complete knowledge of the link. The packet length of RTS and CTS is 160 and 112 bits, respectively, while for data packets length varies from 4000 to 12000 bits. To allow for simultaneous transmissions it is necessary that RTS should be transmitted even if there is ongoing data transmission present. However, we restrain from transmitting RTS if current $\text{Rank}(R_I) = M$. The transmission of RTS using STBC may lead to collisions, packet loss, or both when the $\text{Rank}(R_I) < M$. Using simulations, we found that the impact of such packet loss on performance is insignificant. We are, therefore, more interested in the performance of the protocol on delay and throughput as a function of the system parameters such as traffic load and number of nodes. For the purpose of simplifying analysis, we restrict to the special case which uses DATA-ACK transmission, the bi-directional transmission model. We use RTS/CTS scheme as a feedback mechanism where, in a slow fading environment, RTS/CTS need to be sent only after a long duration. The long enough duration over which one RTS/CTS can be neglected in comparison to the number of data packets send.

We assume that RTS/CTS mechanism is employed just for the channel feedback at sparse intervals. This is a reasonable model for the case of network, where the issues such as hidden terminal is minimal. Thus we can neglect the effect of RTS/CTS on the system in the analysis, by using a bi-directional model, instead of four directional model. The timing diagram of the bi-directional model, with RTS/CTS is shown in Figure 1.

III. CHARACTERIZATION OF THE SYSTEM THROUGHPUT

We assume that N_P transmitter-receiver pairs, having M antennas at each node are uniformly distributed in a toroidal

area A , constructed from a rectangle of dimension $a \times a$. Note that N_P denotes total number of pairs in the system while N_I denotes actual number of interfering transmitters. At any time number of simultaneously transmitting nodes N_I is less than or equal to the total number of transmitters N_P . We assume a slotted system of slot duration σ . We consider single-hop MAC analysis for the protocol discussed in the previous sections in a saturated traffic conditions employing bi-directional model. We take into account the impact of transmission channel and capture effects in an interference environment. We will define various scenarios under which we need to calculate the probability of packet error.

We define probability of packet error when $x\%$ of the total bits in the packet are in error. Define a function $F(L, xL, p) = \sum_{i=0}^{xL} \binom{L}{i} p^i (1-p)^{L-i}$. The function F can be written in terms of the regularized incomplete Beta function, $I_{1-p}(L-xL, xL+1)$. The incomplete beta function $I_p(a, b)$, is given by, $\int_0^p t^{a-1} (1-t)^{b-1}$. Let L_d denote the length of data packet, and L_c denote the length of the control packet. Thus the probability of success for the data packet is given by, $F(L_d, xL_d, p)$, while the probability of control packet success is given by, $F(L_c, xL_c, p)$. The transmission packet errors are due to collision and channel induced errors because of fading. Let the packet error probabilities in these scenarios be given by P_c and P_{ec} respectively. In single antenna systems, usually the collision is defined as packet error because of simultaneous transmission of two packets. In the protocol, the notion of channel collision is different from the traditional definition. We define channel collision as: *the simultaneous transmissions of two nodes, by which the current spatial degree of freedom exceeds available spatial degrees of freedom*. The channel induced errors account for the interference produced by the simultaneous transmissions.

The transmission is controlled by a back-off counter. In the i^{th} transmission attempt, if a successful ACK is not received within $ACK_{timeout}$, then the counter is restarted with the next stage with a random number uniformly distributed in $[0, 2^{i+1}W_0 - 1]$, with W_0 being the value of contention window in the first transmission attempt.

The performance metric we consider here is saturation throughput¹. The saturation throughput A_T of the saturated network is defined as,

$$A_T = \sum_{j=1}^{N_P} \frac{1}{T_{avg}} P_j L_d, \quad (6)$$

where P_j is the probability of successful transmission by node j , T_{avg} is the average total time spent in a successful transmission of packet.

We focus on a particular node r , which acts as a receiver, located at the origin of area $a \times a$, intended to receive signal from transmitter t . Bianchi [7] analyzed saturation throughput of traditional 802.11 protocol by a standard two dimensional Markov chain with no fading. Let $\{s(t), b(t)\}$ denote a two

¹A saturated network is the network where each node always has a packet to transmit.

dimensional process, with $s(t)$ denote the stage of back-off and $b(t)$, the state within a stage. Following key assumptions are used for defining the Markov process:

- 1) The probability τ_j that a station j will transmit in a generic time slot is independent across slots.
- 2) The probability of transmission error $P_{eq,j}$ is independent of erroneous transmissions previously occurred.

Using the results for collision probability in [7], after solving for the invariant distribution of the Markov chain, the exact expression for the probability that node j starts transmitting a packet in any given slot is given by [8]:

$$\tau_j = \frac{2(1 - 2P_{eq,j})}{(W_0 + 1)((1 - 2P_{eq,j}) + W_0 P_{eq,j}((1 - (2P_{eq,j})^w)))}, \quad (7)$$

where $P_{eq,j}$, is the probability of failed transmission of at least DATA or ACK packet and W_0 is the minimum contention window size. The value of τ_j is a function of SNR at the receiver of the transmitter j and $\tau_i, i \neq j$. This interdependency is alleviated by assuming that $\tau_j = \tau, \forall j$, and $P_{eq,j} = P_{eq}, \forall j$ on average. P_{eq} can be considered equivalent to collision probability in [7] and is calculated as in Equation 8.

The wireless channel for a transmitter node at any point of time is undergoing following events, (i) successful transmission, (ii) DATA corruption, (iii) ACK corruption, and (iv) idle slot. We first calculate the probabilities of each of these events. Final values are shown in Table II. To determine the probabilities, we need to calculate channel error probability P_{ec} , the effective error due to DATA corruption and ACK corruption. Let $P_n = P(n \text{ interfering data transmissions take place while a given node is transmitting})$. Let $P_{eq,K}^n$ represent probability of transmission failure of packet length K bits in presence of n interferers where $P_{eq,K}^n = 1 - (1 - P_c)(1 - P_{ec,K}^n)$. The probability of failed transmission includes the probability of collision P_c and probability of error due to channel conditions $P_{ec,K}$. The probability of channel error $P_{ec,K}^n$ is obtained from the bit error probabilities using Table I. Then probability of ACK corruption, occurring exactly after the successful data transmission is given by,

$$\begin{aligned} P_{ack}^n &= P(\text{ACK corrupted}) \times \\ &P(\text{Data correctly transmitted}) \\ &= P_{eq,L_c}^n \times (1 - P_{eq,L_d}^n) \end{aligned}$$

where P_{eq,L_c} denote probability of ACK error recalculated assuming packet length L_c . Thus,

$$P_{eq} = \sum_{n=0}^{M-1} P_n (P_{eq,L_d}^n + P_{eq,L_c}^n (1 - P_{eq,L_d}^n)) \quad (8)$$

The collision occurs if there are already $M - 1$ data transmissions and two simultaneous data transmissions commence in a generic slot. We calculate the collision probability P_c , for various cases in what follows.

A. $N_P = 1$

Notice from the Table I, when number of pairs N_P is less than number of antennas M , the BER is small and hence the

TABLE II
EVENT TABLE FOR TWO WAY CHANNEL

i	Event	Duration d_i	Probability p_i
1	Idle	σ	$(1 - \tau)^{N_P - M + 1}$
2	Error DATA or ACK	$T_{DATA} + SIFS$ $+ ACK_{T_{imeout}}$	P_{eq}
3	Successful Transmission	$T_{DATA} + SIFS$ $+ T_{ACK} + DIFS$	$1 - P_{eq}$

TABLE III
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Data Rate	1 Mb/s	Tslot	0.02 ms
# of pairs	20	P_{ec, L_d}^M	0.2
Packet size	10kb	$SIFS$	10us
Synchronization overhead	0.192ms	T_{ACK}	0.304 ms
p_t/N_0	20dB	M	4
C_{Wmin}	5	C_{Wmax}	10

packet error. In this case with no collision and packet error, $P_{eq} = 0$. From Equation 7, $\tau = \frac{W_0 + 1}{2}$.

By renewal theorem, average normalized throughput, is obtained as,

$$A = \frac{E[\text{Duration of successful transmission}]}{E[\text{Duration of renewal interval}]}$$

$$A = \frac{P_s T_{DATA}}{(1 - \tau)\sigma + P_s(T_{DATA} + SIFS + T_{ACK} + DIFS)}$$

$$= \frac{\tau \times T_{DATA}}{(1 - \tau)\sigma + \tau(T_{DATA} + SIFS + T_{ACK} + DIFS)}, \quad (9)$$

where $P_s = 1 - (1 - \tau)$ is the probability of successful transmission. T_{xyz} is the duration of type xyz packet transmission.

B. $N_P \leq M - 1$

This case is equivalent to N_P independent simultaneous transmissions. Here we assume that Bit Error Rate (BER) is small under the presence of $M - 2$ interferers. Here, using Equation 9 normalized average throughput is, $A' = N_P A$.

C. $N_P \geq M$

When $N_P \geq M$, the possible number of combinations and overlapping of multiple packets is difficult to quantify. Hence we find upper bound for the saturation throughput.

1) *Upper Bound of saturation throughput:* To calculate upper bound, we assume that out of ongoing transmissions, $M - 1$ transmissions are unaffected by each other's transmission. Each of these $M - 1$ transmissions behave as an independent system with $N_P = 1$. The saturated throughput can be obtained from $M - 1$ simultaneous transmissions. From Section III-B, the average normalized throughput of these transmissions is, $A' = (M - 1)A$. We next assume that the M th transmission occurs among remaining $N_P - M + 1$ pairs. Here the idle slot corresponds to no transmission out of $N_P - M + 1$ pairs, whose probability is $(1 - \tau)^{N_P - M + 1}$. Collision probability in this case is the probability of simultaneous transmissions of more than one node out of $N_P - M + 1$ nodes, which is $P_c = 1 - (N_P - M + 1)\tau(1 - \tau)^{N_P - M} - (1 - \tau)^{N_P - M + 1}$. The value of P_{eq} is obtained using Equation 8, with $P_n = 0, n < M - 1, P_n = 1, n = M$ and P_c for the upper bound.

The exact impact of $M - 1$ transmissions in remaining $N_P - M + 1$ transmissions is not known. Hence Equation 10 gives the upper bound. Upper bound A_T^u for the saturation throughput of the system is then given by reward renewal theorem as,

$$A_T^u = \frac{T_{DATA} \times p_3}{\sum_{i=1}^3 d_i p_i} + A', \quad (10)$$

where d_i and p_i denote the duration and probability for the corresponding event number in Table II.

If $N_P \gg M$, the steady state distribution per degree of freedom will be uniform. Thus each degree of freedom can be considered to be independent channel with $\frac{N_P}{M}$ pairs per degree of freedom, assuming N_P is an integral multiple of M for simplicity. Here the idle slot corresponds to no transmission out of $\frac{N_P}{M}$ pairs, whose probability is $p_1 = (1 - \tau)^{\frac{N_P}{M}}$. Collision probability in this case is the probability of simultaneous transmissions of more than one node out of $\frac{N_P}{M}$ nodes, which is $P_c = 1 - (\frac{N_P}{M})\tau(1 - \tau)^{\frac{N_P}{M} - 1}$. By recalculating τ using Equation 7 and P_{eq} using Equation 8, we can derive the saturation throughput as,

$$A_T^u = \frac{T_{DATA} \times p_3 \times M}{\sum_{i=1}^3 d_i p_i} \quad (11)$$

D. Estimation of Medium Access Delay

We define medium access delay as the duration, starting from the transmission of the head of the line packet, till the acknowledgment is received, including retransmission time of the packet. The medium access delay D can be easily calculated as,

$$D = \frac{L_d N_P}{A_T \times \text{DataRate}}. \quad (12)$$

A lower bound on the delay obtained can replacing A_T by the upper bound A_T^u .

IV. PERFORMANCE RESULTS

We perform discrete event simulations in Matlab to simulate a single-hop network of 40 nodes ($N_P = 20$), with $M = 4$ antennas each, distributed uniformly over an area of 20mx20m. Simulation parameters used are given in Table III. The source and destinations are chosen randomly, with the condition that the no source has the same destination. We simulated a network, with the link level property which results in a situation when there are less than $M - 1$ transmissions there is no error. It is also assumed that the rank information is obtained correctly by the transmitter. We compared OMAC protocol with the following: (i) the standard Single Input Single Output (SISO) 802.11 protocol with $M = 1$ and (ii) the 802.11 MAC protocol using MIMO with $M = 4$. The results of this performance study are shown in Figures 2(a) and 2(b). Figure 2(a) shows saturated throughput of the OMAC, SISO 802.11, and MIMO 802.11 cases compared with the analytically derived upper bound for saturated throughput. At low load, OMAC and 802.11 provided the same

throughput whereas with increasing load, OMAC provided better throughput. At saturated load, the simulation throughput remained well within the analytical bound derived using Equation 11. The throughput improvement obtained by OMAC is approximately about 260%. This throughput increase is mainly due to OMAC's capability to exploit the spatial degrees of freedom. Similarly, Figure 2(b) presents the delay performance of OMAC compared with SISO 802.11, MIMO 802.11, and saturated delay bounds from the analytical model. In the case of delay performance, at low load conditions, OMAC and the 802.11 provided lower delay than the SISO 802.11. At saturated load, OMAC provided a much better delay performance which is well bounded within the analytical estimates. Another important performance measure is the utilization of spatial degrees of freedom. We estimated the average number of simultaneous transmissions as a measure of the utilization of spatial degrees of freedom. Figure 3 shows the performance evaluation of the utilization of spatial degrees of freedom achieved by our OMAC protocol. We noticed the utilization of spatial degrees of freedom is as high as as high as 85% at saturation load with OMAC protocol.

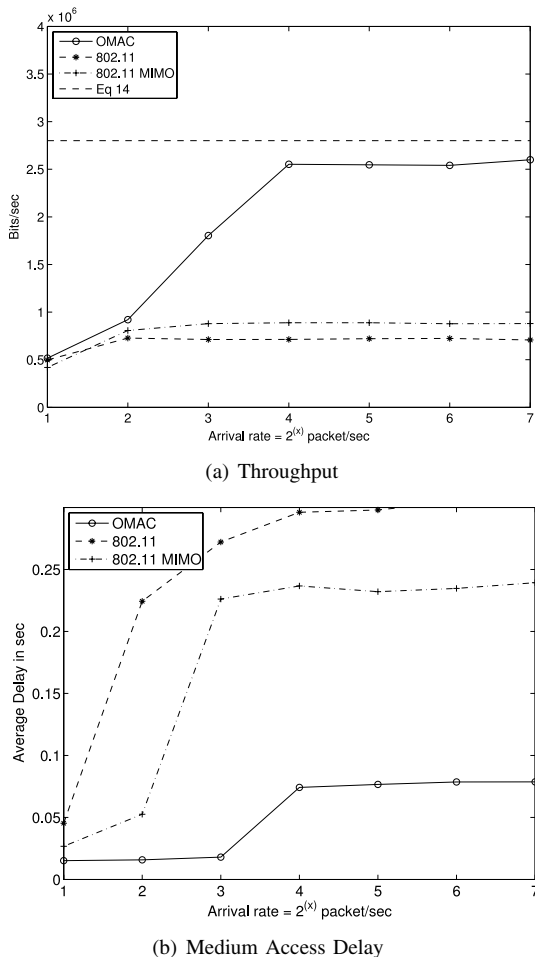


Fig. 2. Model validation with number of nodes $N_P = 20$

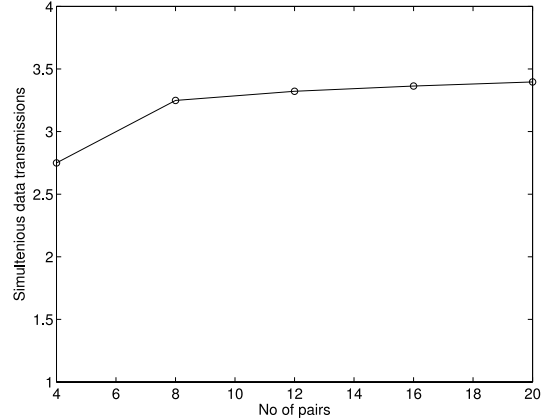


Fig. 3. Average Simultaneous transmissions

V. CONCLUSIONS

In this paper, we propose the Opportunistic MAC (OMAC) protocol, an asynchronous MAC protocol for MIMO ad-hoc wireless network. The key concept of OMAC is the novel physical layer metric, rank of the interference matrix $Rank(R_I)$, that provides an estimate of the use of spatial degrees of freedom in a MIMO system. Use of the $Rank(R_I)$ in a MIMO-adapted carrier sensing based MAC scheme is found to be providing very high utilization of degrees of freedom. Performance evaluation using theoretical analysis and simulation experiments showed that up to 85% of degrees of freedom utilization is achieved when using our OMAC in a 4x4 antenna system.

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