Title
Channel Access Using Opportunistic Reservations and Virtual MIMO

Author
Garcia-Luna-Aceves, J.J.

Publication Date
2008-08-03

Channel Access Using Opportunistic Reservations and Virtual MIMO

Xin Wang [†]
wangxin@soe.ucsc.edu
[†]Computer Engineering Department,
University of California, Santa Cruz
Santa Cruz, CA 95064, USA

J.J. Garcia-Luna-Aceves [†*]
jj@soe.ucsc.edu
[*]Palo Alto Research Center (PARC)
3333 Coyote Hill Road
Palo Alto, CA 94304, USA

Hamid R. Sadjadpour [‡]
hamid@soe.ucsc.edu
[‡]Electrical Engineering Department,
University of California, Santa Cruz
Santa Cruz, CA 95064, USA

***Abstract*— We propose ORCHESTRA, a channel access protocol that uses reservations and virtual MIMO to provide high throughput and bounded channel access delays. Channel access process is divided into a contention-based access period and a scheduled access period. To attain high throughput, nodes build the channel schedule using the contention-based access period, and utilize the spatial multiplexing gain of virtual MIMO links in the scheduled access period. To attain bounded channel access delays, nodes reserve time slots through opportunistic reservations. We evaluate the performance of ORCHESTRA through numerical analysis and simulations, and show that it results in much better throughput, delay, and jitter characteristics than simply using MIMO nodes together with scheduled access (i.e., NAMA) or contention-based access (i.e., IEEE 802.11 DCF).**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) techniques can increase channel capacity significantly through the use of multiple antennas. In a point-to-point MIMO channel, the multiple antenna arrays increase the spatial degrees of freedom (DOF) and can provide spatial multiplexing gain or spatial diversity gain [1]. Consider a system with N_T transmit and M receive antennas, in order to achieve the spatial multiplexing gain, the incoming data are demultiplexed into N_T distinct streams and each stream is transmitted from a different antenna with equal power at the same frequency. Foschini et al. [2] has shown that the multiplexing gain can provide a linear increase in the asymptotic link capacity as long as both transmit and receive antennas increase. In rich multipath environments, the transmitted data streams fade independently at the receiver and the probability that all data streams experience a poor channel at the same time is reduced. This contributes to the spatial diversity gain of the MIMO channel. In order to achieve spatial diversity gain, each stream is transmitted using different beamforming weights to achieve a threshold gain at the specified receiver while at the same time nulling co-existing, potentially interfering transmitter-receiver pairs. The spatial diversity gain can be used to reduce the bit error rate (BER) or increase the transmission range of the wireless links [3]. We denote by H_{ij} the channel coefficient matrix between sender i and receiver j. H_{ij} can be estimated by the receiver through the pilot symbols, but it is unknown at the sender.

Spatial multiplexing and spatial diversity gains cannot be maximized at the same time, and so there is a tradeoff between how much of each type of gain any scheme can extract [1]. In this paper, we use virtual antenna arrays to emulate a MIMO system, which can provide same type of antenna gains and have a higher channel capacity. We propose ORCHESTRA, a channel access protocol that uses reservations and virtual MIMO to provide high throughput and bounded channel access delays. Channel access process is divided into a contention-based access period and a scheduled access period. To attain high throughput, nodes build a channel schedule using the contention-based access period, and utilize the spatial multiplexing gain of virtual MIMO links in the scheduled access period. To attain bounded channel access delays, nodes reserve time slots through opportunistic reservations. Section II provides a summary of related work, and Section III describes ORCHESTRA. Section IV analyzes the frame length, throughput, worst-case channel access delay and convergence time of ORCHESTRA. Section V evaluates the performance of ORCHESTRA under multi-hop scenarios through simulations, and compares it with alternative designs based on the application of MIMO nodes to IEEE 802.11 DCF and a basic schedule-based channel access protocol.

II. RELATED WORK

Sundaresan et al. [4] proposed a fair stream-controlled medium access protocol for ad hoc networks with MIMO links. This work assumes that the receiver can successfully decode all the spatially multiplexed streams when the total number of incoming streams is less than or equal to its DOFs. A graph-coloring algorithm is used to find the receivers that may be overloaded with more streams than they can receive, and then fair link allocation and stream control are applied to leverage the advantage of spatial multiplexing.

SD-MAC [5], NULLHOC [6], and SPACE-MAC [7] all take advantage of spatial diversity. SD-MAC uses the spatial

---

[1] This work was partially sponsored by the U.S. Army Research Office under grants W911NF-04-1-0224 and W911NF-05-1-0246, by the National Science Foundation under grant CNS-0435522, by DARPA through Air Force Research Laboratory (AFRL) Contract FA8750-07-C-0169, and by the Baskin Chair of Computer Engineering. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

degrees of freedom embedded in the MIMO channels to improve the link quality and multirate transmissions. It uses the preamble symbols of each packet to convey the channel gains. RTS and CTS are transmitted using a default rate, while data packets are transmitted using multi-rate transmissions. NULLHOC divides the channel into a control channel and a data channel. It uses RTS/CTS handshake in the control channel to keep track of the active transmitters and receivers in the neighborhood and distributes the required transmit and receive beamforming weights. After a receiver obtains an RTS from the transmitter, it calculates its weight vector to null interfering transmissions and conveys the weights to the transmitter using a CTS. 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. SPACE-MAC uses a single channel for the transmission of control and data packets. A node estimates the channel coefficient after it receives the RTS/CTS packets. When a node other than the designated receiver obtains an RTS, it estimates the effective channel matrix and adjusts the weight vector such that the signal from the sender of the RTS is nullified for the duration of time specified in the RTS duration field. When a node other than the sender of the RTS receives the CTS, it estimates the effective channel and stores the weight vector for the duration specified in the CTS duration field.

The Virtual Antenna Array (VAA) approach was first introduced by Dohler [8]. A base-station array consisting of several antenna elements transmits a space-time encoded data stream to the associated mobile terminals which can form several independent VAA groups. Each mobile terminal within a group receives the entire data stream, extracts its own information and concurrently relays further information to the other mobile terminals. It then receives more of its own information from the surrounding mobile terminals and, finally, processes the entire data stream. VAA offers theoretically much more in terms of capacity bounds and data throughput.

Jakllari et al. [9] proposed a multi-layer approach for ad hoc networks using virtual antenna arrays. By using the spatial diversity gain and cooperative transmission among different nodes, their approach forms a virtual MIMO link that increases the transmission range and reduces the route path length. However, this approach requires the virtual MIMO links to be bi-directional. In addition, when there are not enough collaborating nodes around the receiver, the sender cannot cooperate with other nodes to utilize the spatial diversity gain.

III. ORCHESTRA

A. Motivation

The ergodic (mean) capacity for a complex additive white Gaussian noise (AWGN) MIMO channel can be expressed by [10] [11]: $C = E_H\{log_2[det(I_M + \frac{P_T}{\sigma^2 N_T} H H^\dagger)]\}$, where P_T is the transmit power constraint, N_T is the number of transmit antennas, M is the number of receive antennas, H is the channel matrix, σ^2 is the variance of AWGN and superscript † denotes complex conjugate transpose. E_H denotes the expectation over all channel realizations. This expression for C demonstrates that, under the constraint of constant total transmit power per node, increasing the number of receive antennas increases the system capacity. However, with the increase of the transmit antennas, the system capacity converges to a constant value if the number of receive antennas is fixed. Based on this observation, we consider a simple virtual MIMO system in which each node transmits using only one antenna, and decodes simultaneous transmissions using up to M antennas.

The spatial multiplexing gain of the virtual MIMO link cannot be applied directly to the MAC protocol. When the number of simultaneous transmissions is more than the number of receive antennas, the performance of the decoder decreases and the computational complexity of the receiver increases significantly. To correctly achieve the spatial multiplexing gain, senders need to form a schedule to coordinate the simultaneous transmissions. However, it is impossible to use perfect channel scheduling in a multi-hop ad hoc network, and random channel access has to be used to some extent. Accordingly, ORCHESTRA is built around a hybrid channel-access approach based on opportunistic reservations to leverage the capabilities provided by virtual MIMO links.

B. Channel Organization

The channel is organized into time frames of duration T_f, with each time frame being divided into L time slots. The length of each time slot is T_s. Each node is synchronized on slot systems and nodes access the channel based on slotted time boundaries. Each time slot is numbered relative to a consensus starting point. A time slot is made up of the contention-based access period and the schedule-based access period, as shown in Fig 1-(a). We assume that the channel does not change within a time slot.

C. Contention-Based Access Period

During the contention-based access period, nodes exchange the neighbor information and form the transmission scheduling. It is further divided into a ready-to-receive (RTR) section, a request-to-send (RTS) section and a clear-to-send (CTS) section.

D. RTR Section

A node that determines itself to be the intended receiver of other nodes or observes a broadcast transmission request will identify itself as a *receiver*. The RTR section is used by a receiver j to send an RTR packet that indicates: (a) The current slot t is occupied by j and only the nodes that have packets targeted to j can transmit in slot t; (b) the list of senders that have successfully reserved transmissions in slot t to receiver j; and (c) the number of senders targeted to receiver j (K_s^j). This information helps each sender to decide how many slots it should reserve in a time frame. We denote the overall number of transmission pairs in the two-hop range as K_s, $K_s = \sum_j K_s^j$, then each sender should reserve at least $\lfloor \frac{L}{K_s} \rfloor$ slots in a frame.

Based on the neighbor information collected (see Section III-E), each receiver chooses the time slot it occupies in the next frame and send an RTR packet in the RTR section of that slot. In the first time frame, the RTR section is empty. The length of the RTR section is T_{RTR}, where T_{RTR} is the transmission time for an RTR packet.

E. RTS Section

The RTS section is used to exchange neighbor information and channel-state information. RTS section is made up of multiple mini-slots, as shown in Fig 1-(b). The length of the RTS section is $L_{\mathrm{RTS}} = M \times T_{\mathrm{PS}} + R \times (T_{\mathrm{RTS}} + T_{\mathrm{PS}})$, where T_{PS} is the transmission time for pilot symbols, T_{RTS} is the transmission time for an RTS packet.

If a sender i observes an RTR packet that indicates m ($m \leq M$) senders (including i) have successfully reserved transmissions, it will just send the pilot symbols in the first M mini-slots of the RTS period, according to the sequence indicated in the RTR packet. The pilot symbols are needed by the receiver to estimate the channel status and utilize the spatial multiplexing gain. Otherwise it will randomly pick up one of the remaining R mini-slots and send an RTS packet along with the pilot symbols.

The RTS packet includes: (a) The intended receiver j, (b) the past bandwidth share of link (i, j) (B_{ij}), (c) the antenna weight W_i to be used by sender i to receive the CTS packet, (c) a one-hop neighbor list and whether a one-hop neighbor is a receiver. B_{ij} is defined as the percentage of successful transmissions of link (i, j) over the past 5 time frames, and W_i is initialized randomly by the sender i. Nodes form the two-hop topology information through the exchange of one-hop neighbor list. If a node does not receive any packets from a neighbor during two time frames, it removes the neighbor from the one-hop neighbor list.

After receiving the pilot symbols from sender i , receiver j uses the pilot symbols to estimate the channel matrix between i and j ($H_{i,j}$).

F. CTS Section

The CTS section is used to form the transmission scheduling and broadcast the scheduling results through the transmissions of CTS packets. It includes three steps:

1) Receiver-based channel scheduling formation: Each receiver forms a channel scheduling $S(t)$ based on the information collected in the RTS section. t is the data slot number of the schedule-based transmission period. $t \in 1, \ldots, N_{data}$; and N_{data} is the length of schedule-based transmission period, which will be discussed in Section III-H. We define two distinct links $i = (s_i, r_i)$ and $j = (s_j, r_j)$ are *interfere* with each other if the distance of either one the two pairs $(s_i, r_j), (s_j, r_i)$ is less than the node's transmission range. The indicator function $I(i, j)$ equals 1 if link i, j interfere with each other; otherwise, it equals zero. We formulate the transmission scheduling problem as follows:

$$\begin{array}{lll} & max \sum_{t=1}^{N_{data}} \sum_{i=1}^{|S(t)|} log B_i & \\ s.t. & I(i,j) = 0, & \forall i, j \in S(t), i \neq j \\ & |S(t)| \leq M, & \forall t \in 1, \ldots, N_{data} \end{array} \tag{1}$$

where B_i is the past bandwidth share of link i, it is obtained through the exchange of the RTS packets.

The objective of the optimization is to achieve the proportional fairness among different links. The first constraint ensures the scheduling is collision free. The second constraint guarantees the number of simultaneous transmissions is at most equal to the number of receive antennas.

2) Distribution of slots reservations: After receiver j forms the scheduling $S(t)$, it reserves a slot for $S(t)$ in the next time frame. Each node maintains a reservation table to record how each slot in a time frame is reserved.

The maximum distance between two reserved slots is $D_{\mathrm{rmax}} = \lfloor \frac{D_{\max}}{T_s} \rfloor$ to satisfy the delay constraint of the specific application ($D_{\max}$). On the other hand, the distribution of slots reservations influences the jitter of the channel access delay. In the ideal case, the reserved slots for each receiver j should be uniformly distributed, the distance between two reserved slots is $D_r = \lfloor \frac{LK_s^j}{K_s} \rfloor$. However, it may not always be satisfied. Based on the above two considerations, we formulate the problem of reserved slots selection as follows:

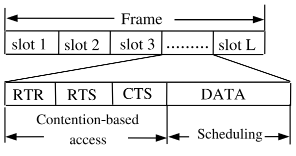
$$\begin{array}{ll} min & ||t_{j+1} - t_j| - D_r|, \forall t_j \in R_t, \forall t_{j+1} \in \overline{R_t} \\ s.t. & |t_{j+1} - t_j| < D_{\mathrm{rmax}} \end{array} \tag{2}$$

where R_t is is the set of the previous reserved slots. For each $S(t)$, receiver j tries to reserve a time slot t_{j+1} in the next frame, whose distance between one of the previous reserved slots t_j is closest to the optimal distance D_r. The maximal delay constraint is needed to be satisfied at the same time. If a node cannot find an unoccupied slot that satisfies the delay constraint, it will drop the packet at the head of the packet queue silently.

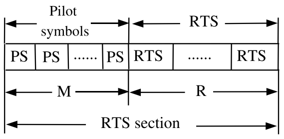
3) CTS transmission : To avoid the collisions of CTS packets from different receivers, each receiver j utilizes the spatial diversity gain to transmit the CTS packet to each selected sender respectively according to the sequence of $S(t)$. The CTS packet includes the channel scheduling $S(t)$, and the achieved spatial multiplexing gain (G_{sm}) for $S(t)$. We first define the *collision-free transmission antenna weight condition* as follows:

$$\begin{array}{rcl} W_i^H H_{i,j} W_j & = & 1 \\ W_i^H H_{i,n} W_n & < & \varepsilon, \quad n \neq j, 0 < \varepsilon \ll 1 \end{array} \tag{3}$$

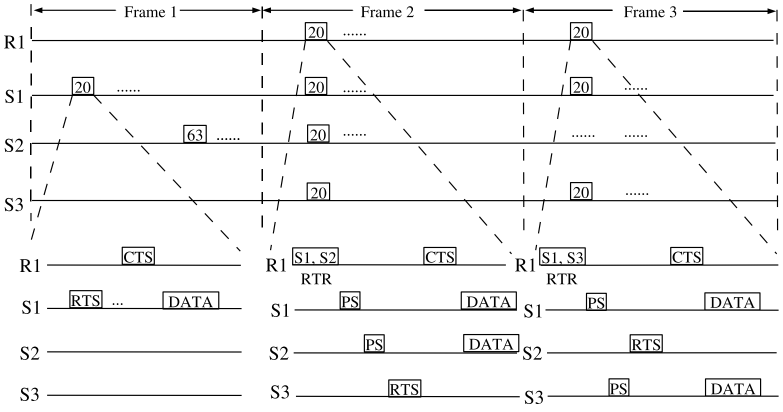
where W_i is the transmission antenna weight of sender i, W_j is the receive antenna weight of receiver j, and n are the active receivers in the transmission range of sender i. ε is a small



(a) Frame and time slot structure



(b) RTS section



(c) Channel access example

Fig. 1.

value that satisfies:

$$\text{SINR}_n = \frac{\varepsilon P_i L_i}{\sum_{k\neq i} P_k L_k + \sigma_n^2} < \text{SINR}_{threshold}, \tag{4}$$

In the above equation, σ_n^2 is the background or thermal noise power at the front end of the receiver n; P_i is the transmission power and L_i is the corresponding path loss factor of i; $\text{SINR}_{threshold}$ is the minimum value of signal to interference plus noise ratio (SINR) that is needed to correctly decode the transmission signal; and *collision-free transmission antenna weight condition* guarantees that after the transmission antenna weight adjustment of the sender, only the targeted receiver can receive the packet and the other active transmissions will not be corrupted.

In ORCHESTRA, given that receiver j already has the antenna weight (W_i) used by the sender i to receive the CTS packet, which is stated in the RTS packet, it calculates the antenna weight (W_j) used to transmit the CTS packet according to the *collision-free transmission antenna weight condition*. The approach used in ORCHESTRA to adjust the antenna weights of the CTS packets differs from the approaches used in NULLHOC and SPACE-MAC in that (a) ORCHESTRA does not require that $W_i^H H_{i,n} W_n = 0$, and (b) the probability that two senders have similar antenna weights for CTS packet reception is very small, because W_j is a $M \times 1$ vector initialized randomly by the sender i. This guarantees that, even when the channel matrices are highly correlated for different senders ($H_{i,j}$ and $H_{i,n}$), we can still find a feasible solution for Equation 3, thus reducing the possible collisions of CTS transmissions.

Because the number of simultaneous transmissions in the two-hop range is at most twice the number of receive antennas (M), at most $2M$ CTS packets should be sent. The length of the CTS section is $2M \times T_{\text{CTS}}$, where T_{CTS} is the transmission time for a CTS packet.

G. Conflict Resolution

Upon receiving CTS packets from different receivers, nodes compare the G_{sm} and follow the scheduling results with the largest G_{sm}. When the G_{sm} of two CTSs are the same, then the links that are in conflict will not be used.

H. Scheduled Access Period

In the scheduled access period, the senders that successfully receive the CTS packets transmit simultaneously using a single antenna. The length of schedule-based access period (T_{data}) is the remaining part of the time slot, that is, $T_{data} = T_s - T_{\text{RTR}} - M \times T_{\text{PS}} - R \times (T_{\text{RTS}} + T_{\text{PS}}) - 2M \times T_{\text{CTS}}$.

The schedule-based access period is made up of multiple data slots. The length of a data slot (T_{payload}) is the time needed to send a data packet with maximum payload length. The number of the data slots (N_{data}) is $N_{\text{data}} = \lfloor \frac{T_{\text{data}}}{T_{\text{payload}}} \rfloor$.

We use an example to illustrate the channel access procedure, as shown in Fig 1-(c). We assume that three nodes $S1$, $S2$, $S3$ have packets to send to receiver $R1$, which has two receive antennas. $S3$ does not have packets for $R1$ until the second frame. In all the slots of the first time frame, the RTR section is empty. $S1$ and $S2$ randomly select a slot to transmit the RTS packet, after getting the confirmation from $R1$, $S1$ and $S2$ transmit in the schedule-based access period. The channel access procedure of the first time frame is similar to the the 802.11 DCF . In the second frame, $R1$ reserves the slot 20 and send the RTR packet, which indicates $S1$ and $S2$ have successfully reserved the transmissions. Then $S1$ and $S2$ just need to transmit the pilot symbols in the RTS section and transmit simultaneously in the scheduling-based access period. $S3$ randomly picks up a mini-slot in the RTS section to transmit the RTS packet and does not receive the confirmation from $R1$. In the slot 20 of the third frame, $S1$ and $S3$ are selected, while $S2$ sends the RTS packet.

IV. PERFORMANCE ANALYSIS

In this section, we numerically analyze the frame length, throughput, worst-case channel access delay and convergence time of ORCHESTRA. Due to the page limit, we just enumerate the important conclusions. The proof of the lemmas and more detailed discussions can be found in [12].

A. Frame Length

Lemma 4.1: The worst-case minimum frame length needed for each node to unicast successfully in one slot every frame in ORCHESTRA is $\lceil \frac{Min\{d^2+1,N\}}{M} \rceil$, where d is the maximum node degree (number of neighbors a node has) of the network, N is the number of nodes in the network, M is the number of receive antennas.

Lemma 4.2: The worst-case minimum frame length for each node to unicast successfully to each of its neighbors once every frame in ORCHESTRA is $\lceil \frac{Min\{2(d^2-d+1),N\}}{M} \rceil$ slots.

B. Worst-Case Channel Access Delay

At the stationary state, each node should reserve one slot in every time frame. The worst channel access delay is decided by the following case, node i reserves the first slot of the current frame and the last slot of the next frame.

$$d_{max} = 2L - 2 \tag{5}$$

V. PERFORMANCE COMPARISON

We compare the performance of ORCHESTRA with two alternative designs: DCF-MIMO and NAMA-MIMO.

In DCF-MIMO, an RTS/CTS handshake is used to eliminate the hidden terminal effect and pilot symbols are sent in the RTS packet to the receiver. The RTS/CTS packets are sent with a low transmission rate (R_{basic}), while the DATA/ACK packets are sent with a high transmission rate (R_{data}) which utilizes the spatial multiplexing gain of MIMO links. DCF-MIMO is the most direct extension of IEEE 802.11 DCF for MIMO system.

NAMA-MIMO extends the NAMA scheme [13]. NAMA uses a hash function that takes the node identifier and the current time slot number as input to derive a random priority for every neighbor within two hops. If a node has the highest priority, it can access the channel within the corresponding time slot. The advantage of NAMA is that it incurs very small communication overhead in building the dynamic channel access schedule. NAMA-MIMO extends NAMA by using the spatial multiplexing gain in the payload transmission of each slot.

A. Physical Layer Transmission Rate Comparison

To make a fair comparison between the MIMO and the virtual MIMO system, we need to derive an approximate physical layer rate mapping relationship. The physical layer transmission rate is $Rate = \mathrm{C} \times \mathrm{BW}$, where C is the channel capacity, BW is the channel bandwidth. We assume the MIMO and the virtual MIMO systems have the same total bandwidth and unit variance noise. There are no spatial interferences and both systems can achieve their channel capacity upper bounds. Hence, from the expressions for channel capacity and transmission rate presented before, we can get an approximate relationship of total transmission rate of virtual MIMO (R_{vmimo}) and MIMO (R_{mimo}) system: $\frac{R_{\text{vmimo}}}{R_{\text{mimo}}} \approx \frac{log(1+P)}{log(1+P/M)}$.

Based on the default transmission power and data rate settings in Qualnet simulator [14], which are indicated in Table I, we can get the transmission rate comparison of MIMO and virtual MIMO systems with different number of antennas, as Fig 2 shows. It demonstrates that MIMO system always achieves a lower total transmission rate than virtual MIMO system. The ratio of R_{vmimo} over R_{mimo} increases with the number of antennas but decreases with the additional transmission power.

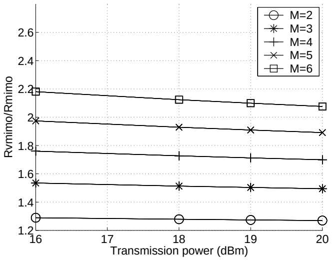


Fig. 2. Tx rate comparison of MIMO and virtual MIMO

TABLE I

TX POWER AND TX DATA RATE RELATIONSHIP

Tx power(dBm)	Tx data Rate (Mbps)
20.0	6, 9
19.0	12, 18
18.0	24, 36
16.0	48, 54

Now we assume that R_{mimo} is fixed at 54 Mbps and vary the number of receive antennas. Then, according to Fig 2, we can get the corresponding transmission rate of the virtual MIMO system (R_{vmimo}) and maximum transmission rate of each link (R_{link}), as Table II shows.

TABLE II

TX RATE OF VIRTUAL MIMO SYSTEM

Number of antennas(M)	R_{vmimo} (Mbps)	R_{link} (Mbps)
2	69.63	34.82
4	95.04	23.76
6	117.75	19.63

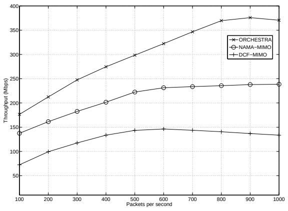
B. Simulation Settings

We assume that each receiver has four receive antennas and uses 802.11a as the physical layer. The MIMO transmission rate is 54 Mbps. The transmission power is 16dBm. The receive threshold for 54Mbps data rate is -63dBm, the corresponding transmission range is around 40m. All these simulation parameters are default settings in Qualnet [14]. According to Table II, the total transmission rate of the virtual MIMO system is 95.04Mbps, while the maximum transmission rate for each link is 23.76Mbps. The duration of the simulation is 100 seconds. A time frame is made up of 100 time slots ($L = 100$). The simulations are repeated with ten different seeds to average the results for each scenario. We set the path loss factor $\alpha = 4$, the number of mini-slots in the RTS section (R) is 5, and the delay constraint (D_{max}) is 20ms.

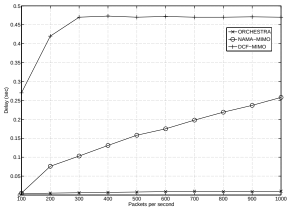
We evaluate the performance of ORCHESTRA under two scenarios: multiple-sender single-receiver topologies and random topologies. We omit the simulation results of multiple-sender single-receiver topologies due to the page limit. They can be found in the technical report [12].

C. Random Topology

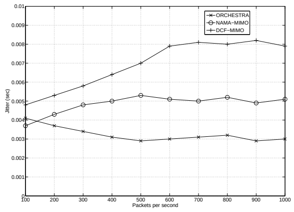
We generate 10 topologies with 50 nodes uniformly distributed across a 500 × 500 square meters area. We set up 20 CBR flows between randomly selected sender-receiver pairs, such that senders and receivers are always more than two hops away from each other. The packet length of the CBR flows is 1024 bytes. The simulation results is shown in Fig 3, which demonstrates that even in random topology, ORCHESTRA can still increase at least two times of the system throughput, while attain bounded channel access delay at the same time.



(a) System Throughput



(b) Delay



(c) Jitter

Fig. 3. Random topology

ORCHESTRA outperforms NAMA-MIMO because of three reasons. First, in NAMA, a node may probabilistically derive low priority for a long period of time and never get access to the channel. Second, there may be chain effects to the channel access opportunities, in which the priorities of nodes cascade from high priority to low priority across the network. Chain effects reduce the spatial reuse of the system. Third, channel bandwidth may also be wasted when a node does not have data to send in the allocated time slot. Because of the wasted bandwidth causing starvation to the nodes with traffic, NAMA interacts badly with certain applications that are sensitive to the delay, such as TCP congestion control and AODV route update mechanisms.

VI. CONCLUSION

We proposed a joint PHY/MAC optimization approach based on spatial diversity gain to reduce the collisions of control packets, while utilizing the spatial multiplexing gain to increase the transmission rates of data packets. The advantage of ORCHESTRA is that enjoys the high throughput merit of probabilistic channel access schemes, the bounded access delay characteristics of reservation-based schemes, and multiplexing gains attainable with virtual MIMO. ORCHESTRA is suitable for ad hoc networks in which voice and data services must be provided, and takes advantages of multiple antennas much more efficiently than simply applying MIMO techniques at the physical layer to conventional contention-based or dynamic-scheduling channel access schemes.

REFERENCES

[1] L. Zheng and D. Tse, “Diversity and Multiplexing: A Fundamental Tradeoff in Multiple-antenna Channels,” *IEEE Transactions on Information Theory*, vol. 49(5), pp. 1073–1096, May 2003.

[2] G. Foschini, G. Golden, R. Valenzuela, and P. Wolniansky, “Simplified Processing for High Spectal Efficiency Wireless Communication Employing Multi-element Arrays,” *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1841–1852, Nov. 1999.

[3] J. Anderson, “Antenna Arrays in Mobile Communications: Gain, Diversity, and Channel Capacity,” *IEEE Antennas and Propagation Magazine*, vol. 42, pp. 12–16, Apr 2000.

[4] K. Sundaresan, R. Sivakumar, M. A. Ingram, and T.-Y. Chang, “A Fair Medium Access Control Protocol for Ad-hoc Networks with MIMO links,” in *Proceedings of IEEE INFOCOM*, March 2004, pp. 2559–2570.

[5] M. Hu and J. Zhang, “MIMO Ad Hoc Networks: Medium Access Control, Satuation Throughput, and Optimal Hop Distance,” *Special Issue on Mobile Ad Hoc Networks, Journal of Communications and Networks*, 2004.

[6] J.C.Mundarath, P. Ramanathan, and B. Veen, “NULLHOC: a MAC protocol for adaptive antenna array based wireless Ad Hoc networks in multipath environments,” in *Proceeding of IEEE Global Telecommunications Conference*, 2004, pp. 2765–2769 Vol.5.

[7] J.-S. Park, A. Nandan, M. Gerla, and H. Lee, “SPACE-MAC: Enabling Spatial Resuse using MIMO Channel-aware MAC,” in *Proceeding of IEEE International Conference on Communications*, 2005.

[8] M. Dohler, *Virtual Antenna Arrays*. King’s College London: Ph.D. Thesis, 2003.

[9] G.Jakllari, S.Krishnamurthy, M.Faloutsos, P.Krishnamurthy, and O.Ercetin, “A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks,” in *Proceedings of IEEE INFOCOM*, 2006.

[10] G. J. Foschini and M. J. Gans, “On Limits of Wireless Communications in a Fading Environment when using Multiple Antennas,” *Wireless Personal Communications*, no. 6, pp. 311–355, 1998.

[11] E. Telatar, “Capacity of Multi-antenna Gaussian Channels,” *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–595, November 1999.

[12] X. Wang, J. J. Garcia-Luna-Aceves, and H. R. Sadjadpour, “Channel Access Using Opportunistic Reservations and Virtual MIMO, http://www.soe.ucsc.edu/˜wangxin/virtual_mimo_report.pdf,” in *UCSC Technical Report*, 2007.

[13] L. Bao and J. J. Garcia-Luna-Aceves, “A New Approach to Channel Access Scheduling for Ad Hoc Networks,” in *ACM Seventh Annual International Conference on Mobile Computing and networking(Mobicom)*, 2001.

[14] Qualnet Simulator, “Scalable Network Technologies, http://www.scalable-networks.com/.”