Exploiting Diversity Gain in MIMO Equipped Ad hoc Networks

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***Abstract*—MIMO links coupled with space-time codes can combat fading and hence can significantly increase the capacity of ad hoc networks. This ability of providing " diversity gain" can increase the capacity of ad hoc networks. Currently, most of the studies on MIMO links systems are focused on the physical layer without taking into consideration the intricacies of a network-wide deployment. In this work we study the benefits of a network-wide deployment of MIMO links in mobile ad hoc networks. In particular, we examine the trade-offs between using the possible diversity gain for an increase in range or an increase in rate. We make minor modifications to traditionally used MAC and routing schemes popularly considered for ad hoc networks and perform extensive simulations to understand the above trade-offs. We quantify the performance trade-offs in terms of the achieved throughput and end-to-end latency. Our studies can serve as a precursor to the design of adaptive schemes that can exploit the achievable diversity to increase range/rate depending on the scenario at hand.**

I. INTRODUCTION

Multiple Input-Multiple Output (MIMO) antenna technology can offer a significant enhancement of communication quality at the physical layer. MIMO antennas create "independent" channels, by *exploiting* multipath propagation. When correlated signals are transmitted through these channels, the variance in SNR (signal-to-noise ratio) drops at the receiver; consequently the bit error rate of receptions at a fixed SNR value decreases significantly. This gain in signal quality due to MIMO systems is called "*diversity gain*". *Space-time codes* can be used in conjunction with an antenna array to enable diversity gain at the physical layer; the performance improvement on a MIMO link using these codes have been well explored and quantified [2], [13], [14], [5].

Due to diversity gain, the SNR requirement for achieving a target bit-error-rate (BER) decreases. One can exploit this reduced SNR requirement in multiple ways. The two possibilities that we consider in this paper (assuming nodes do not perform power control to change their transmission powers) are: *i)* the signals transmitted by a node can be decoded by other nodes that are beyond the range of omni-directional or single-input single-output (SISO) communications with the same BER; this is a direct consequence in the reduced SNR requirement. *ii)* given that the signals are received with lower bit error rates (BER) as compared to the SISO case, the transmitter nodes can use more aggressive modulation schemes and increase their transmission bit rates. By properly exploiting these two advantages one can significantly improve the end-to-end performance in a multi-hop wireless network.

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In this work our goal is to study how the MIMO diversity gain affects the end-to-end performance in a multi-hop network. Leveraging the diversity gain at the higher layers in a multi-hop network has not been studied to date. Our motivation is to understand the *relative* merits of exploiting the aforementioned two advantages possible with diversity gain. We consider the two possibilities, namely the **increase in range** and the **increase in rate**, at the physical layer in an ad hoc network. We carry out exhaustive network level simulations to quantify the trade-offs between the two possibilities in various scenarios. Intuitively, increasing the rate does not allow a maximal increase in range and therefore results in a higher number of hops than with a case where the diversity gain is exclusively used for increasing range. We quantify the performance in terms of the end-to-end throughput and latency by exploiting the diversity gain to provide a combination of differing rate and range enhancements. We believe that our measurements will provide insights that will aid the design of adaptive protocols that maximally exploit diversity gain in MIMO equipped ad hoc networks.

We organize the rest of the paper as follows. In Section II we provide background on MIMO systems and describe relevant related work. In Section III we explain our constructions for the physical, MAC and routing layers. In Section IV we provide the simulation details, present our results and elaborately discuss their significance. Finally, we conclude in Section V.

II. BACKGROUND AND RELATED WORK

In this section, first, we briefly discuss how diversity gain is achieved using space-times codes with MIMO antennas; next, we describe related previous work.

MIMO Diversity Gain: A node with multiple antennas transmits symbols on each antenna element with equal power. If the fading characteristics of the parallel channels formed among each pair of transmit and receive antennas are sufficiently different, the channels are "independent".

Diversity gain exists when correlated symbols are transmitted on each antenna element, and the process offers an increase in the signal SNR at the receiver. The diveristy gain depends onthe number of antenna elements [4]. To achieve diversity gain, the receiver should have the channel state information (CSI) with regards to each transmitting antenna element.

Space-time block codes (STBC) have been proposed to aid the creation of diverse channels [2], [13]. With STBC the modulated symbols are mapped onto a space-time code matrix, which generates the code symbols by exploiting both temporal and spatial diversity. Using STBC, a number of code symbols equal to the number of transmit antennas are transmitted simultaneously, on the different antenna elements. These symbols are combined at the receiver; the combining reduces the variations in the reception SNR significantly. STBC thus improves robustness to channel impairments.

Related Work: Within the last decade, a multiplicity of protocols have been proposed to exploit the beamforming capability of antenna arrays (for example [9], [10], [6]). By beamforming in a particular direction, antenna arrays offer higher ranges and an increased number of simultaneous communications in a unit area. "Directional" MAC protocols were designed in order to exploit directional communications and achieve high spatial reuse at the MAC layer. To make these protocols feasible, synchronized schemes to perform neighbor discovery and maintenance have been proposed [6]. At the routing layer, directional communications were exploited to support multipath routing for load balancing [9], as well as for bridging partitions using the high transmission range that is possible using antenna arrays [10].

The MIMO capability of antenna arrays has largely been studied at the physical layer and over a single link. There are few research efforts to date, that have studied MIMO in a multihop network from the perspective of higher layers. In [12], Sundaresan et.al. proposed a scheduling algorithm to offer fair medium access in a network where nodes are equipped with MIMO antennas. The model under study provides a simple abstraction of the physical layer properties of MIMO antennas. At the routing layer, Sundarasan et.al., proposed a routing scheme to exploit MIMO gains [11]. The idea is to adaptively switch the transmission/reception strategy using MIMO (i.e. to switch between the different strategies of exploiting MIMO gains) so that the aggregate throughput at the routing layer is increased. At each hop along a route this decision is made dynamically based on network conditions such as node density and traffic load. However, the approach proposed approach does not incorporate realistic physical layer models.

At the transport layer, Toledo et.al. investigated TCP performance over MIMO communications [15]. Focusing on the two architectures previously proposed to exploit spatial multiplexing and diversity gains (namely BLAST and STBC), the authors study how the ARQ and packet combining techniques impact on the overall TCP performance. Their results indicate that, from the standpoint of TCP performance, the enhanced reliability offered by the diversity gain is preferable to the higher capacities offered by spatial multiplexing. Recently, in [7], the challenges that arise due to cross layer interactions with the use of MIMO have been articulated. In contrast to the discussion in this work, our goal is to study the trade-offs between the exploitation of the diversity gain for rate versus range.

III. Our Models

In this section we describe our network and communication models. We delineate how the diversity gain is incorporated into this model for an increase in communication range and/or transmission rate.

All nodes in our network model are equipped with four-element antenna arrays (i.e. the number of transmit and receive antennas on the endpoints of all MIMO links in the system is 4). The system operates on a single frequency band. When we use the term "independent channels", we refer to the independent propagation paths between each pair of transmit-receive antenna elements, as opposed to frequency channels that are non-overlapping. In the mobile scenario, each node moves towards an arbitrarily chosen point within the area of deployment with a constant speed; after reaching this point it starts moving towards another arbitrary point on the region. The model causes continuous changes in the network topology. Our simulation-specific parameters are listed in Section IV.

Physical Layer Model: Upon the reception of a packet, a receiver computes the received signal-to-noise ratio (SNR_{rcv}). based on the received signal power and noise. For the packets having an SNR_{rcv} greater than a preset threshold Th the number of bit errors is computed; if this value is smaller than a defined BER threshold the received packet is successfully retrieved. Packets having an SNR_{rcv} that is lower than Th are treated as noise packets. When the power of noise packets is very weak, the receiver can simultaneously receive another packet (with a strong signal) from a nearby neighbor; this enables spatial reuse in the network [1].

Nodes exchange pilot tones prior to MAC layer packet exchange. We implement the range extension offered by diversity gain as a *temporary decrease* in the value of Th at the receiver. As per this model, nodes that receive the pilot tones from the transmitter node u will lower their SNR threshold while receiving successive MAC layer packets from u. In other words, the MAC packet from node u will be received successfully if its SNR_{rcv} is greater than a lowered threshold Th' given by:

$$Th' = Th - DivGain(dB) \tag{1}$$

The value of $DivGain$ in Eqn. 1 depends on the number of antennas on the endpoints of the MIMO link and the STBC in use. In this study, we employ the generalized complex orthogonal space-time block coding scheme introduced by Tarokh et al., which can be used with more than two antennas at the nodes [14]. These codes combine the coding at the transmitter with linear processing at the receiver (which requires CSI at the receiver). Using this scheme, a diversity gain of ∼15dB is achieved with four transmit antennas using QPSK modulation [5]. In our simulations we use this value to represent the diversity gain for 4x1 MIMO. We assume high SNR and our results provide an upper bound on the enhancement offered with MIMO diversity gain. In reality, the diversity gain is lower with lower SNRs.

We compute the range possible with the new threshold Th', based on the model in [8], as follows.

$$d_{DG} = d_{SISO} \cdot 10^{DivGain/10\alpha} \tag{2}$$

, where d_{SISO} is the range with SISO communications, d_{DG} is the extended range and α is the path loss exponent. For α=3 and $DivGain$= 15 in Eqn. 2, we find that d_{DG}=d_{SISO}x$10^{3.16}$. This value implies that, when the diversity gain offered by 4x1 MIMO systems is used only to provide an extension in range, the communication range can be increased by as much as 3.16 times as that with SISO communications.

Modulation Scheme	Gain (Rate)	Gain (Range)	Rate	Range
SISO (BPSK)	0 dB	0 dB	1 unit	1 unit
BPSK	0 dB	15 dB	1 unit	$\sim$3.1 units
QPSK	2 dB	13 dB	2 units	$\sim$2.7 units
8-PSK	5 dB	10 dB	3 units	$\sim$2.1 units
16-PSK	10 dB	5 dB	4 units	$\sim$1.4 units

TABLE I
ACHIEVABLE RATES AND RANGES DUE TO DIVERSITY GAIN WITH DIFFERENT MODULATION SCHEMES.

Modulation Scheme	Diversity Gain (Range / Rate)	Rate	Range
SISO(BPSK)	0 dB / 0 dB	1 unit (6 Mbps)	1 unit (100m)
BPSK	15 dB / 0 dB	1 unit (6 Mbps)	3.1 units ($\sim$310m)
QPSK	13 dB / 2 dB	2 units (12 Mbps)	2.7 units ($\sim$270m)
8-PSK	10 dB / 5 dB	3 units (18 Mbps)	2.1 units ($\sim$210m)
16-PSK	5 dB / 10 dB	4 units (24 Mbps)	1.4 units ($\sim$140m)

TABLE II
ACHIEVABLE RATES AND RANGES DUE TO DIVERSITY GAIN WITH DIFFERENT MODULATION SCHEMES.

As mentioned earlier, diversity gain can also be exploited for increasing nodes' transmission rates. The decrease in the SNR requirement in satisfying a certain bit error rate allows nodes to use more aggressive modulation schemes such as QPSK, 8-PSK or 16-PSK (to transmit more bits per symbol than BPSK); the bit rates with these schemes are higher by factors of 2, 3, 4 respectively, as compared to BPSK. The SNR values that facilitate switching between these modulation schemes is available in [8]. We incorporate these values in our experiments. In cases where the diversity gain is greater than the SNR needed for a denser modulation scheme, we employ the excessive gain to offer an extension in range as possible. Table I lists the ratios of data rates and communication ranges for different modulation schemes, and the fraction of diversity gain that is utilized to realize these rate and range values.

MAC Layer Model: At the MAC layer we use the IEEE 802.11 MAC protocol in the DCF mode; we employ 802.11g owing to the extended regime of data rates that it offers. Given the data rates that can be used with 802.11g, we use 6 Mbps bit rate for the SISO case, and compute the rates with the rest of the schemes based on Table I. Nodes exchange pilot tones followed by RTS/CTS control frames prior to data communication, and each data transmission is followed by an ACK. The packets exchanged in a data communication are depicted in Figure III. For each scheme, all MAC layer control packets (RTS,CTS,ACK) are transmitted with the corresponding rates (e.g. 18 Mbps with 8-PSK), as opposed to the base rate of 6 Mbps.

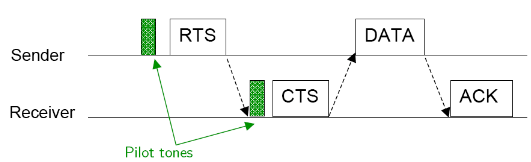


Fig. 1. The packet train at the MAC layer.

Modeling the Routing Layer: In this study, we use the AODV routing protocol [3]. AODV is an on-demand protocol, where the routing activities are initiated prior to data transfer, by broadcasting route request (RREQ) messages. Broadcasts are done at the rate at which data communications are to be performed. Pilot tones are sent prior to each broadcast. With AODV, each node keeps a routing table, where one entry per destination is stored. Upon receiving an RREQ, nodes look up their routing tables to initiate a route reply (RREP) back to the source. An entry in the routing table expires if it is not used for a pre-specified duration; then the corresponding route becomes stale. Expired routes are deleted from the routing table and new RREQs are broadcast.

AODV also supports periodic local broadcast of neighborhood information for link maintenance. Nodes broadcast Hello packets every "Hello Interval" period; if no Hello packet is received for a constant multiple of "Hello Interval" seconds, connectivity to this neighbor is assumed to be lost and new RREQs are broadcast. Upon link/node failures, route error (RERR) packets are broadcast by local neighbors; therefore, all nodes within the communication range are notified about the link in error.

IV. SIMULATIONS

Simulation Setup: We perform our simulations on OPNET v.11 [1]. OPNET enables the realistic modeling of the wireless communication characteristics that were described in Section III. In all scenarios, all nodes are equipped with four-element antenna arrays. Nodes transmit at a fixed power of 0.5 mW, using which the SISO communication range is around 100 m. at 6 Mbps bit rate using isotropic antennas. Nodes are placed randomly in a 600m x 600m flat terrain, which corresponds to 6x6 unit area with the SISO range of 100 m. Nodes are static unless specified otherwise. In all simulations, nodes generate 512-byte packets with a constant rate; the packet generation rate is scenario-dependent and is varied to simulate different network loads. The source-destination pairs are spread randomly over the network and the routing is performed using the AODV ad hoc routing protocol.

We simulate the five different schemes (as listed in Table I in Section III) that exploit the diversity gain, and we compare the end-to-end performance using each method in various scenarios. The exact rate and range values employed in our simulations are listed in Table II.

Parameters and Metrics: We study the dependence of network performance on the following parameters.

(a) Network load. We vary the network load by varying the number of source-destination pairs and the packet generation rate at individual nodes.

(b) Node density. We experiment with different node densities within considered area.

(c) Speed of Nodes. Nodes continuously move towards a randomly chosen point with a constant speed of 10 m/sec.

We quantify the performance with each scheme in terms of the following metrics:

(1) Average number of hops per route. Routes with fewer hops are deemed more efficient by AODV, due to the fact that the vulnerability of the path to delay and failure increases with each additional hop.

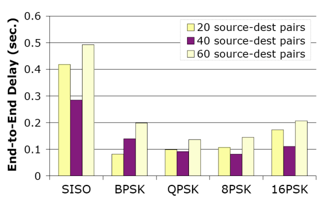
(2) End-to-end throughput. We measure the number of packets that are successfully transmitted to their destination at the routing layer; we average these values over all source-destination pairs to find the representative value in a given scenario.

(3) Average end-to-end delay of data packets. We compute an average over all end-to-end delays experienced by successful packet deliveries. This value includes all possible delays due to route discovery, queuing delays, contention, and retransmissions at the MAC layer.

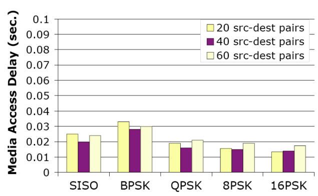
(4) Average channel access delay. The total of queue and contention delays, *and* the delay due to RTS/CTS exchange experienced by data packets prior to transmission.

A. Simulation Scenarios, Results and Discussions:

1. Effect of Network Load: To simulate varying network load, we change the number of source-destination pairs in the network. In the scenarios with many sources, each source generates fewer packets per second, to avoid over-congesting the network (this would skew the results).



(a) Average End-to-End Delay



(b) Channel Access Delay

Fig. 2. Average end-to-end delay and medium access delays with different number of source-destination pairs in a 180-node network.

Figure 2(a) shows the average and-to-end delay with the different ways of exploiting the diversity gain, as the number of source-destination pairs are changed between 20 and 60 in a 180-node network. Nodes generate 2 packets/sec. except in the scenario with 20 sources, where each source generates 5 packets/sec. We observe that, at all values of load, the schemes that exploit diversity gain show significantly lower delays as compared to the network that uses SISO communications. With all schemes, except for the one which uses the diversity gain to exclusively achieve an increase in range (denoted as BPSK), the end-to-end delay decreases from 20 to 40 sources. This is a direct consequence of two factors (i) the reduced rate of transmission when we consider a higher number of sources and (ii) the reduction in the average hop count when a larger number of source destination pairs are chosen for a given population of nodes.

For BPSK, end-to-end delay increases with the higher number of sources. Through careful inspection, we find that this uncommon behavior of BPSK is due to the broadcasting overhead introduced with diversity gain, when diversity gain is used for increasing the range. With diversity gain, the SNR threshold is reduced for the broadcast packets, which are always preceded with a pilot tone. The extension in range thus formed increases the contention region and thus, the number of contending nodes for each instance of channel access. This effect is depicted in Figure 3. With the increased range the communicating nodes are farther apart ($d_2 > d_1$ in Figure 3). Thus, with carrier sensing they silence a larger fraction of the nodes while they are communicating. If the overall rate of transmission is not higher, this could, in some cases, degrade performance. This effect increases per-hop channel access delay, which is shown in Figure 2(b) for the same network considered for generating Figure 2(a).

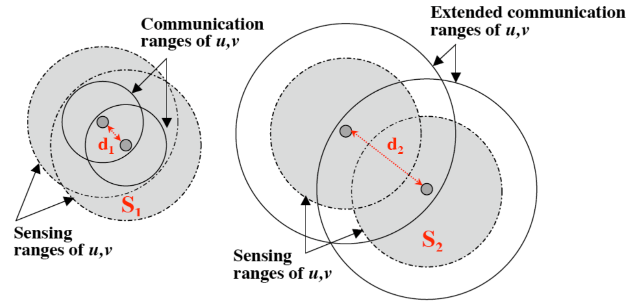
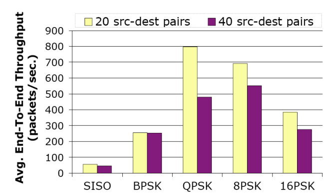
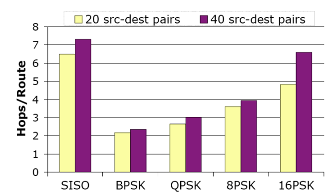


Fig. 3. The extension in range causes higher contention.



(a) Average End-to-End Throughput



(b) Average Hop Count

Fig. 4. Effect of network load on end-to-end throughput in a 180 node network.

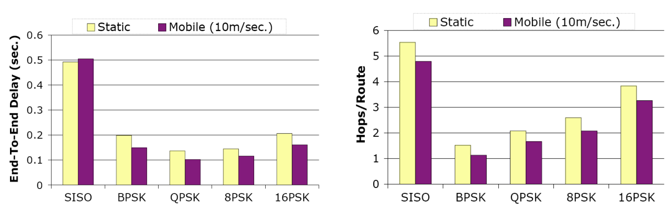
We also measure the end-to-end throughput with 20 and 40 source-destination pairs in a 180-node network; in the former scenario each source generates 200 packets/sec. and in the latter sources generate 50 packets/sec. The loads are high enough to drive the network to saturation. The average hop counts increase slightly for a larger number of sources for all schemes (Figure 4(b)); this can be directly attributed to congestion during the route discovery process. The best trade-offs are achieved with QPSK and 8-PSK in the two respective scenarios. On the other hand, these are sensitive to an increase in load. BPSK is affected to a smaller extent due to lower hop count. Similarly 16-PSK is more robust to an increase in load due to lower transmission times. However, on an absolute scale, they still perform worse than 8-PSK and QPSK in the scenarios considered. On the other hand, with the use of MIMO, paths become more resilient to mobility and wireless channel impairments.

2. Effect of Mobility: Next we observe the effect of mobility on the end-to-end performance with the considered schemes. We plot average end-to-end delay experienced by data packets in static and mobile scenarios in Figure 5(a). We observe that the average end-to-end delays and average hop counts decrease with mobility. This interesting phenomenon has been also observed in [3], and it arises due to better load balancing offered with node mobility. With SISO communications the end-to-end delay remains high in spite of the reduction in hop count. The shorter transmission range and the low transmission rate with SISO render this scheme more vulnerable to path failures.

3. Effect of Node Density: We also measure the same metrics on AODV routes in networks with different node densities. Figure 6(a) shows the average end-to-end throughput in a network with 20 source-destination pairs, in networks consisting of 180 and 360 nodes, respectively (corresponding to node densities of 5 and 10 nodes/unit area on the 6x6 area of deployment). Each node generates 200 packets/sec. The average throughput increases slightly at higher densities. Although QPSK performs best in the low density scenario, its performance degrades at the higher density; in the latter scenario 8-PSK overperforms the other schemes. The cause of the behavior of QPSK is the increase in contention (a larger number of nodes are shut off during each access instance due to carrier sensing) owing to an increase in range (QPSK scheme achieves a larger range than 8-PSK) at higher densities. The corresponding end-to-end and channel access delay values in this scenario are shown in Figure 7(a) and Figure 7(b). The average hop count of the paths found by each scheme is depicted in Figure 6(b).

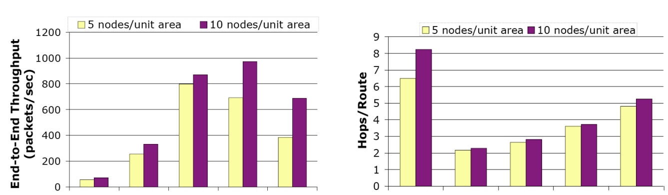
V. Conclusions

The diversity gain offered by MIMO antennas reduces the bit error rate on a communication link for a given SNR value. In this work, we study how this gain can be translated to a better performance at the higher layers in a multi-hop network. Using appropriate modulation schemes, we leverage the diversity gain for increasing the communication range, the transmission bit rate, or both. We measure the end-to-end performance of each scheme in different scenarios where we vary the offered load, node mobility, and node density. We interpret the simulation results to identify the scheme that offers the best end-to-end performance in the scenario studied. We believe that the results reported in this paper will serve as a guideline for the development of adaptive protocols to be used in ad hoc networks equipped with MIMO antennas.



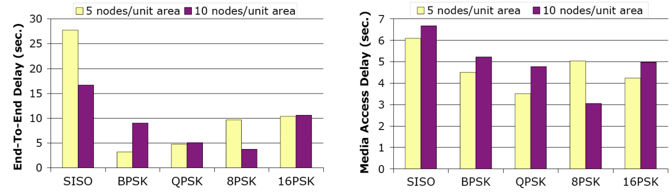
(a) Average ETE Delay (b) Average Hop Count

Fig. 5. Effect of node mobility on end-to-end delay.



(a) Average End-to-End Throughput (b) Average Hop Count

Fig. 6. Average end-to-end throughput achieved and the average hop count of the routes found by each scheme at different node densities.



(a) Average End-to-End Delay (b) Average Channel Access Delay

Fig. 7. End-to-end and per-hop channel access delays experienced by each scheme at different node densities.

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