Routing in Ad-hoc Networks with MIMO Links*

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Abstract

Smart antennas include a broad variety of antenna technologies ranging from the simple switched beams to the sophisticated digital adaptive arrays. While beam-forming antennas are good candidates for use in strong line of sight (LOS) environments, it is the multiple input multiple output *(MIMO) technology that is best suited for multipath environments. In fact, the MIMO links exploit the multipath induced rich scattering to provide high spectral efficiencies. The focus of this work is to identify the various characteristics and tradeoffs of MIMO links that can be leveraged by routing layer protocols in rich multipath environments to improve their performance. To this end, we propose a routing protocol called* MIR *for ad-hoc networks with MIMO links, that leverages the various characteristics of MIMO links in its mechanisms to improve the network performance. We show the effectiveness of the proposed protocol by evaluating its performance through* ns2 *simulations for a variety of network conditions.*

1 Introduction

Smart antennas are multiple element arrays (MEAs) that include a broad variety of antenna technologies ranging from the simple switched beams to the sophisticated digital adaptive arrays. Most of the related work in the ad-hoc research community has focused thus far on the design of medium access control [8, 10, 3, 7] and routing protocols [9, 2] with switched-beam or directional antennas. While switched beam antennas have pre-determined beam patterns and are simple in the transceiver complexity, they are also limited in their performance. They provide significant performance improvement in strong *line of sight* (LOS) environments where they increase the spatial reuse in the network owing to directional transmissions. However, they suffer significantly in rich multipath environments (typical in indoor environments, urban outdoor environments, etc.) where signal scattering and fading causes loss of energy in the received beam. Adaptive array antennas are more sophisticated than the switched beam, since they are capable of *adapting* their beam pattern in response to channel conditions to improve the quality of the link, i.e. maximize the *signal to noise* (SNR) of the link.

In addition to the above smart antenna technologies, recent years have also witnessed the growth of another technology, popularly called as the *multiple input multiple output* (MIMO) technology. While adaptive arrays merely mitigate the impacts of multipath fading, MIMO systems actually exploit rich scattering and multipath fading to provide high spectral efficiencies (bits/s/Hz) that comes at the cost of no increased power or bandwidth [5]. In fact, these high spectral efficiencies can be obtained even without the knowledge of channel state information (CSI) at the transmitter unlike adaptive arrays. MIMO links provide two options for their mode of operation: (i) they can be used to provide increased capacities on the link which is referred to as *spatial multiplexing*, or (ii) they can be used to increase the reliability of the link by exploiting *diversity* to decrease the bit-error rate. Being the most sophisticated of the smart antenna technologies, MIMO links have become extremely popular and have made their way into the WLAN and WIMAX standards (IEEE 802.11n and 802.16). However, to leverage the true potential and unique capabilities of MIMO links in ad-hoc networks, it is arguable that design of tailored protocols is necessary. In [12], the authors propose a MAC protocol for ad-hoc networks that leverages the physical layer capabilities of MIMO links, with the focus being predominantly on the spatial multiplexing capability of MIMO links.

The focus of this work is to go one step further and explore the various capabilities of MIMO links but from the perspective of routing layer protocols. We identify whether and how each of the capabilities can translate to improved performance at the routing layer. Specifically, we make the following contributions:

- We identify the capabilities of MIMO links and capture their relevance to routing layer protocols.

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- We analyze the relative tradeoffs of exploiting the different capabilities of MIMO links.
- We propose a reactive routing protocol whose components are built on the insights gained from the analysis, and hence leverage the PHY layer characteristics in their operations to improve network performance.

Briefly, we identify two fundamental capabilities of MIMO links, namely spatial multiplexing and diversity that can be exploited by the routing layer protocols in their operations. However, since these two capabilities cannot be fully leveraged at the same time, it becomes necessary to investigate the relative trade-offs between spatial multiplexing and diversity, in order to determine the optimal strategy of operation for improving the aggregate network throughput. To this end, we study the benefits and drawbacks of both the strategies from the perspective of routing layer protocols. The study incorporates practical considerations in determining the optimal strategy of operation. A routing protocol is then proposed with components built on the insights gained from the study. The corresponding cross-layer support required from the MAC layer is also identified and accommodated in the design. The effectiveness of the components in the proposed solution is then comprehensively evaluated through simulation studies.

The rest of the paper is organized as follows. In Section 2, we present the background material on the various capabilities of MIMO links. We analyze the relative trade-offs of the two strategies from the perspective of routing protocol operations in Section 3. Section 4 proposes the routing protocol whose components optimally exploit the two strategies based on network conditions. We evaluate the performance of the proposed protocol over a comprehensive set of network scenarios in Section 5. Finally, we discuss related work in Section 6 and present conclusions in Section 7.

2 Preliminaries

In this section, we provide some physical layer background material on the characteristics of MIMO links and outline their capabilities and trade-offs.

A MIMO link consists of multiple element arrays at both ends of the link. The significance and importance of MIMO links is felt in rich multipath environments where switched beam antennas are not effective and adaptive arrays can merely mitigate the negative impacts of multipath. A MIMO link is capable of operating in two modes (strategies), namely spatial multiplexing and diversity.

The gain associated with spatial multiplexing is referred to as the spatial multiplexing gain. Spatial multiplexing gain is defined as the asymptotic increase in the capacity of the link for every 3 dB increase in SNR [14]. This gain can be achieved when the transmit array transmits multiple "independent" streams of data, with each stream being transmitted out of a different antenna with equal power, at the same frequency, same modulation format, and in the same time slot. At the receiver array, each antenna receives a superposition of all of the transmitted data streams. However, each stream generally has a different "spatial signature" due to rich multipath, and these differences are exploited by the receiver signal processor to separate the streams. This multiplexing gain can provide a linear increase (in the number of elements) in the asymptotic link capacity, which is given by the following equation [5],

$$C \approx min(M, N) \log_2(1+\rho) \tag{1}$$

where M and N correspond to transmitter and receiver antenna elements and ρ represents average SNR at any one receive antenna.

The gain associated with diversity is referred to as the diversity gain. The rich multipath helps the transmitter data streams fade independently at the receiver and hence the probability of all the data streams experiencing a poor channel at the same time is significantly reduced, thereby increasing the communication reliability. This contributes to the diversity gain. For a transmit array to provide diversity gain, the data streams transmitted from the different antenna elements must be dependent. Space-time codes are used for this purpose. Diversity gain relates to the reduction in the variance of the SNR at the output of the combiner, relative to the variance of the SNR prior to combining. The reduction in variance depends on the diversity order. The maximum diversity order afforded by a MIMO link with M transmit antennas and N receive antennas is MN. In practical lossy channels, diversity can help significantly reduce the bit error rate (BER) on the link. At high SNR, this reduction in BER (p) as a function of the diversity order (d) can be given as [14],

$$p \approx \frac{1}{SNR^d} \tag{2}$$

An increase in diversity gain comes at the cost of a reduction in rate and hence the multiplexing gain, thereby leading to a fundamental trade-off between the two strategies [14]. The increased reliability provided by diversity gain can be used in one of three ways, (i) reduce p on the link, (ii) for a required p on the link, the increased reliability provided by diversity can be translated to an increase in the SNR at the output of the combiner, which can then be used for increasing the communication range of the link, and (iii) for a given p and SNR requirement, the transmit power consumption can be minimized. Since power consumption minimization is an orthogonal direction of optimization, we focus only on the first two methods of leveraging diversity gain in this work with aggregate network throughput being the parameter of optimization.

In the rest of this paper, we refer to the spatial multiplexing strategy as MUX, diversity with reduced BER as DIV-BER and diversity with increased communication range as DIV-RANGE for simplicity. Specifically, at the PHY layer all nodes in the network employ spatial multiplexing (eg. VBLAST [4]) for communication in MUX, while they employ diversity (eg. space-time block codes, STBC [1]) in both DIV-RANGE and DIV-BER. The difference in the strategies arises from how and which specific gains are leveraged. In MUX, the routing protocol uses omni-directional communication range for route discovery, resulting in routes with all omni-links on which spatial multiplexing is performed (referred to as "rate" links) during data transfer. In DIV-RANGE, diversity and hence SNR gain is exploited by the routing protocol in route discovery itself, resulting in routes composed of links with larger communication ranges ("range" links). However, in DIV-BER, omni-directional communication range is first used to obtain routes with omni links, with diversity being exploited later on for data transfer, thereby reducing the BER on the link ("reliable" links). While DIV-BER and DIV-RANGE both exploit diversity, the difference arises from whether diversity is exploited in the route discovery component or not. Further, the area of inhibition due to a transmission is lesser in DIV-BER than in DIV-RANGE. While the same transmit power is used in both cases, since the links are much shorter in DIV-BER (higher SNR), the probability of capturing a packet at the receiver is much larger in DIV-BER, thereby providing better spatial reuse. Finally, none of the strategies assume feedback of any channel state information (CSI) from the receiver to transmitter on the links.

3 Practical Considerations

In this section, we discuss the impact of several practical considerations on the different strategies. Specifically, in addition to the lossy nature of links common in wireless environments, we consider varying density (average node degree) and mobility in ad-hoc networks. Simulations results from *ns2* are used for the study with aggregate network throughput being the metric of interest. Briefly, 100 nodes are considered in a 2-d grid whose area is varied in order to vary density with the default being 1000m by 1000m. The default number of flows, mobility and packet loss probability on the links are 30, 0 m/s and 0% respectively unless specified otherwise. Each flow is a CBR flow using UDP and generating data of packet size 1KB at the rate of 100 Kbps on a 2 Mbps channel. Each node is equipped with two element array. DSR is used as the reactive routing protocol with MUX, DIV-RANGE and DIV-BER being incorporated as outlined in Section 2. The range extension function f is assumed to be linear in the rest of this paper. It is more than linear only for very high SNR's and is a reasonable assumption for moderate-high SNR's. Random waypoint mobility model is used for generating scenarios involving mobility. IEEE 802.11b in the DCF mode is used as the MAC protocol.

3.1 Density

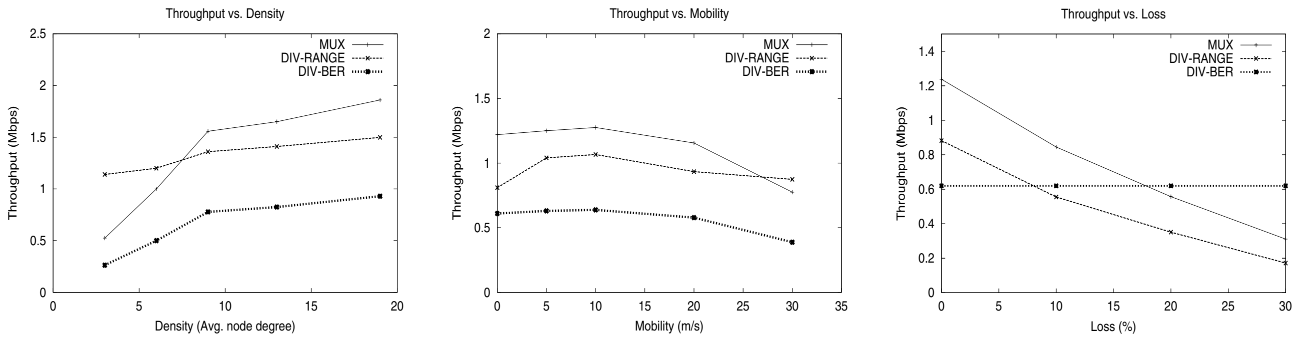
Partitions are a possibility in ad-hoc networks and can disrupt communication due to the lack of a route to the destination. They may be caused due to the sparse nature (density) of the network or due to mobility of the nodes. In cases of mobility, there is a finite probability for the partition to be bridged back again due to node mobility itself. However, the case of partitions in static sparse networks is much more severe since it disrupts communication permanently. Hence, in this subsection we focus on partitions resulting in sparse static networks and postpone the impact of mobility to the next subsection.

While MUX can increase throughput, it cannot increase the communication range and hence operates using the omni-directional communication range. Thus, in static sparse networks, the network graph may not be connected in MUX, resulting in the possibility of no routes existing for some of the flows. This leads to a degradation in aggregate network throughput. DIV-BER still uses the same omni-directional communication range and hence suffers from the same problem as MUX. DIV-RANGE on the other hand, has the potential to bridge partitions through its increased communication range. However, it suffers from the reduced spatial reuse resulting from the increased communication range. Thus, while DIV-RANGE is a better option at low network densities where the ability to bridge network partitions outweighs the reduced spatial reuse, this is not true at high network densities. This can be observed from the results in Figure 1(a). Since the links are assumed to be non-lossy, this makes DIV-BER a poor candidate.

Hence, the optimal strategy with respect to varying node density would be to use DIV-RANGE at lower network densities and MUX at higher network densities. More specifically, DIV-RANGE must be used only by those nodes that would not be able to deliver the packet to the next hop towards the destination using MUX. This would keep the reduction in spatial reuse due to increased communication range to a minimum while at the same time helping all sources obtain a route to their respective destinations in the network.

3.2 Mobility

Mobility is an inherent component of ad-hoc networks. Increased speeds increase the number of route errors,



a) Density (Load = 30 flows) b) Mobility c) Loss (Load = 15 flows)

Figure 1. Impact of Practical Components on Network Throughput

thereby increasing the duration for which a flow remains without a route to its destination. This in turn leads to a degradation in throughput. In addition, reactive routing protocols such as DSR might purge all packets which are bound to use a recently failed link during the propagation of the route error towards the source. Thus, the bandwidth resources used by the packets before being purged are wasted. Once again, to isolate the impact of mobility on the different strategies, we assume the links in the network to be almost lossless. In this context, the following can be shown.

Proposition 1

$$P_{l\_db} < P_{l\_dr} < P_{l\_s}$$

where P_{l_db}, P_{l_dr} and P_{l_s} are the probabilities of a link going down due to mobility in DIV-BER, DIV-RANGE and MUX respectively. [Proof available in [11]]

This implies that the impact of mobility is greatest on MUX at higher speeds followed by DIV-RANGE and DIV-BER. The links in DIV-BER operate on BERs well below the threshold and can hence sustain increased communication ranges during mobility without bringing the link down. In DIV-RANGE, the increased communication range gives the node more area to move about without breaking the link when compared to MUX.

However, the throughput results presented in Figure 1(b) indicate trends contrary to expectation, with DIV-BER performing the worst. Since the links are considered to be non-lossy, DIV-BER suffers a degradation in rate compared to MUX. However, the increase in reliability helps sustain the links longer during mobility, but then results in routes with increased range per hop (number of hops remaining unaltered), thereby resulting in highly sub-optimal routes. These sub-optimal routes tend to degrade performance more than the case wherein route failures occur, however resulting in new (better) routes to be formed. It is also interesting to note that MUX outperforms DIV-RANGE for most of the mobilities. This is because the region silenced by a transmission is more in DIV-RANGE due to the increased communication range. This in turn increases the number of contending nodes to any node and hence increases the number of collisions due to distributed MAC operations. This would also trigger more route failures, thereby overcompensating for the increased robustness to mobility. However, this increased number of collisions is not dependent on mobility and is a constant impact for a fixed load. Hence, as mobility increases, DIV-RANGE's increased robustness to mobility helps it outperform MUX.

MUX, performing the best under most mobility conditions, is the optimal base strategy of operation. However, the ability to provide increased communication ranges using diversity should be used in tandem with MUX to alleviate its vulnerability to route failures.

3.3 Link quality

In ad-hoc networks, due to the multi-hop nature of the flows, packets that are received in error and dropped (due to time-correlated fading) closer to the destination, end up wasting bandwidth resources utilized along the path. This leads to a degradation in the end-end throughput.

In order to determine the impact of wireless channel effects in isolation, we do not consider mobility in these evaluations. The results for the different strategies are plotted as a function of the packet loss rates in Figure 1(c). It can be seen that both MUX and DIV-RANGE suffer degradation in throughput with increasing packet error rates since neither of them is targeted towards increasing the reliability of the link. DIV-BER increases the reliability of the link, albeit at the cost of rate as in DIV-RANGE. The result in Figure 1(c) indicates that DIV-BER provides a steady performance with increasing packet error rates. This is because the decrease in BER resulting from the diversity order of 4 (2 elements) is sufficient to handle packet error rates as high as 30% easily. DIV-BER shows better performance than MUX at packet error rates higher than 20%, although it suffers at lower packet error rates.

Hence, the appropriate strategy would be to use MUX as long as packet error rates are negligible, and have mechanisms to detect persistent channel errors and switch to DIV-BER to increase reliability.

In summary, we find that MUX serves to be the best strategy in static networks with high density as long as the loss rates are low-moderate. In addition, we also find that DIV-RANGE is a beneficial option to be considered in the presence of low network density, high mobility and small loss rates, with DIV-BER being considered for moderate-high loss rates.

4 MIR Routing Protocol

In this section we present the MIMO routing protocol called *MIR*, which is an on-demand (reactive) routing protocol. The goal of MIR is to exploit the benefits of the different MIMO strategies in an optimal manner to provide the best network performance. In the previous section, we saw that no single strategy performs the best over different network conditions of varying density, mobility and link quality and also identified the optimal combination of spatial multiplexing and diversity strategies for the different network conditions. MIR is thus an adaptive routing protocol that adapts between the different strategies based on the network conditions and does so in a transparent fashion. Note that, switching between strategies at a node can be achieved through software adaptation without additional hardware circuitry. However, in realizing the adaptation, there arise several challenges which are outlined below followed by the description of the protocol itself.

4.1 Challenges

Since a specific combination of strategies is required for different network conditions, the challenges that arise in each of them are varied and hence considered separately.

4.1.1 Density

We had seen that while MUX is the appropriate strategy for dense networks, DIV-RANGE is a more favorable option for sparse networks where it might not be possible to obtain routes with omni-directional communication ranges. Furthermore, not all regions of the network have the same density of nodes; while some regions might be densely populated, others may be sparsely populated. Also, the goal is to obtain routes that support high rate and allow for maximum spatial reuse in the network. This indirectly means that the number of range links in the route should be kept to a minimum. So the key question is that, *how should the combination of the two strategies be used in the determination of routes?*

The simplest approach would be to issue a route request using the MUX scheme. The routes discovered in this scheme would consist of all rate links. However, if such a route does not exist, the next route request can be issued using DIV-RANGE. There are two problems with this scheme when there exists no route to the destination with pure rate links; (i) we would be unnecessarily doing a MUX based route request while we could have directly done a DIV-RANGE based route request. This increases the delay in discovering a route, which in turn is dependent on the route request timeout value (minimum of $2\frac{T}{K}h$ time units, where T is the omni-directional transmission time for a packet, h is the average hop length and K is the number of elements); and (ii) the resulting route will be one with predominantly range links and not the one that provides maximum spatial reuse and high rate. Thus, the main challenge here is to obtain the route that provides maximum spatial reuse and rate while at the same time trying to keep the route discovery latency as close as possible to that of the MUX scheme.

4.1.2 Mobility and Link Quality

We have seen that diversity strategy by virtue of using increased communication ranges (as in DIV-RANGE) or increased link reliability (as in DIV-BER), reduces the probability of link failures due to mobility and channel degradation respectively. Hence, MIR's goal is to detect link breakages due to mobility and channel degradation proactively and switch from multiplexing to diversity. The increased communication range or the increased reliability will be exploited to increase the longevity of the link during mobility and channel degradation respectively, which can in turn be used to find an alternate path even before the link breaks. However, there are several associated challenges. It becomes necessary to (i) identify and react to link losses resulting from mobility and persistent channel degradation since switching to diversity for a contention loss would only reduce rate unnecessarily, (iii) prevent unnecessary route switches due to short-term (transient) mobility and channel degradation, (iii) determine the appropriate number of elements to be used towards diversity, since the additional elements used would only further reduce rate without any benefits, and (iv) ensure that an alternate route is obtained before the existing route actually fails.

4.2 MAC Layer Support

The routing protocol in isolation or in co-ordination with the MAC protocol, decides on the strategy to be employed by the node based on the network conditions. However, it is the MAC protocol that is responsible for communicating the decision to the PHY layer and ensuring that the communication takes place using the appropriate strategy for maximum benefits. Irrespective of the strategy employed, the PHY layer receiver must be aware of the strategy being used by the transmitter. Only then will it be able to decode the packet using the appropriate decoding strategy. This information exchange is achieved with the help of MAC layer. The MAC transmitter always transmits the preamble of the packet using diversity (STBC) in which it conveys the strategy to be employed for the actual packet transmission. Since a route can be comprised of both rate (multiplexing) and range/reliable (diversity) links, a receiver cannot determine which strategy to receive a packet on apriori. This is because, the receiver does not know which of its neighboring transmitters is going to transmit and also the strategy that is going to be used by the transmitter. To overcome this problem, the transmitters and receivers use STBC as the invariant strategy for the preamble to account for both rate and range/reliable links. Further, the preamble would convey the actual strategy that will be used by the transmitter for the rest of the packet. In order for the receiver to be able to estimate the channel and use it in its receiver processing, a training sequence is added to the front of the preamble.

Another important role of the MAC layer is to determine the minimum range extension factor with which a packet can be received on a range link. This would help the routing protocol in choosing routes with maximum spatial reuse as we shall see later in this section. Recall that the function f that characterizes range extension factor is linear in the number of elements. Thus, when a packet is transmitted through DIV-RANGE using K elements, it can reach upto K hops. However, at the end of the packet, the node adds $K-1$ short preambles, each being transmitted-received at unity rate similar to the packet but using lesser number of elements ($[1, K-1]$) and hence lower diversity order. These preambles correspond to the different $K-1$ range extensions and carry the respective extension information in them. Only a node within the i^{th} hop will be able to decode the preamble that was transmitted-received using i elements with a diversity order of i^2. By this method, each node keeps track of the minimum range extension ([1,K]) with which the packet was received from the upstream node and stamps it on the packet to be used by the routing layer.

4.3 Routing Protocol Components

The routing strategies in MIR apply to on-demand (reactive) routing protocols that involve route discovery (involving route request and response phases) and maintenance phases. While the inferences drawn from Section 3 apply to proactive routing protocols as well, the design of the routing mechanisms themselves have to be tuned in order to be ap-

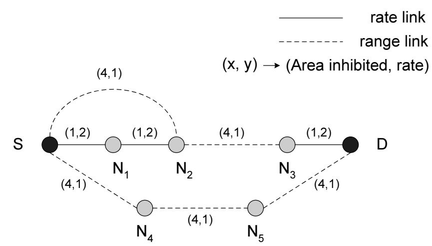


Figure 2. Illustration

plicable. We present MIR as a source-driven reactive routing protocol (such as DSR). However, the protocol components are also applicable to table-driven reactive protocols such as AODV, etc. with minor modifications. Route discovery and maintenance form the two main components of a reactive routing protocol, under which we consider the following five components: route metric, route request, route response, route failure detection during mobility and channel degradation, and route maintenance.

4.3.1 Route Metric

The goal of the route discovery component is to obtain "quality" routes through a careful use of the different strategies irrespective of the density in the network. We define "quality" of a route as its ability to allow for maximum spatial reuse in the *network* while at the same time incurring low multi-hop relaying burden and providing high rate for the *flow* itself. Hence, we consider a two-tuple route metric $Q(R)$ (=($Q_n(R)$,$Q_f(R)$)) for a route R as the combination of network ($Q_n(R)$) and flow ($Q_f(R)$) metrics. This is similar to the routing metrics considered in the widest-shortest routing paradigm in the Internet. We consider $Q_f(R)$ to be the minimum of the rates used by the strategies employed on the links in the path. $Q_n(R)$ can be captured by the total area inhibited (along with duration of inhibition) when a packet travels *along the path* from source to destination. Using $Q(R)$, routes are chosen lexicographically, based on a low network metric; if the network metrics are the same, a high flow metric is used. Though $Q(R)$ is biased toward the network metric, optimizing $Q_n(R)$ indirectly means that the number of range links as well as the number of hops in the route should be kept low. This, in turn also indirectly favors the flow in obtaining a higher rate on the path. The choice of the routing metric itself is not closely tied to the routing strategy and is hence open to further research.

$$Q_n(R) \quad = \quad \sum_{i=1}^{h} \frac{Area\ inhibited\ by\ i^{th}\ hop\ transmission}{Rate\ of\ transmission\ at\ i^{th}\ hop}$$

$$Q_n(R) \quad = \quad \sum_{i=1}^{h} \frac{f_i^2}{r_i} \; ; \quad Q_f(R) = min\{r_i\}$$

where f_i and r_i are the range extension factor and rate of transmission at the i^{th} hop of a h hop route respectively, both being normalized to the corresponding values of an omni-directional transmission. Thus, as long as a "quality" path to the destination exists with all rate links or minimal range links, it should be determined by the routing protocol. For the simple topology in Figure 2 where two elements (extension factor of two) are used, we have three possible routes from source S to destination D, namely, $\{S, N_1, N_2, N_3, D\}$, $\{S, N_2, N_3, D\}$ and $\{S, N_4, N_5, D\}$. The two-tuple metric for the 3 routes are (5.5,1), (8.5,1) and (12,1) respectively. Hence, while several routes exist, the routing protocol should identify the route with the best metric (minimal impact from range links), namely $\{S, N_1, N_2, N_3, D\}$ in our example that has a single range link.

MIR uses a route discovery procedure whose two main components are (i) propagation of route request that keeps the route discovery time small, and (ii) route reply propagation and route selection that help obtain quality routes.

4.3.2 Route Request

Every node on receiving a route request packet, goes ahead and propagates the request on the maximum range possible using DIV-RANGE. Whenever a route request is transmitted using DIV-RANGE, it is done on all elements (K), and can thus reach upto K hops. With support from the MAC layer through the use of short preambles, each node keeps track of the minimum range extension ([1,K]) with which the request was received from the upstream node. Whenever a node forwards a request, in addition to adding itself to the source route, it also adds the extension factor of the link with its upstream node. The source route carried on the request packets will thus "initially" consist of predominantly range links (eg. $\{S, N_2, N_3, D\}$ in Figure 2). However, when the destination receives the request packet with a range factor of say i ($i \epsilon [1, K]$), it waits for approximately $\phi i T$ seconds (where T is packet transmission duration on an omni link, ϕ is a constant that accounts for the additional time taken to access the channel due to contention) to help the nodes in the last set of i hops including itself to bridge/patch their local upstream range links with rate links. The time spent by the destination in waiting coupled with route response propagation time is sufficient to helps the other upstream nodes to have their local upstream range links bridged (replaced) with rate links if permitted by the underlying topology (eg. $\{S, N_2\}$ can be bridged as $\{S, N_1, N_2\}$). The bridging is achieved as follows. Each intermediate node (say N_2) after forwarding a route request keeps track of the reverse path to the source along with its metric ($\{N_2, S\}$ with metric (4,1)). Later on, if it receives another request with a much better route back to the source ($\{N_2, N_1, S\}$ with metric (1,2)), then it replaces the local route it has stored for the source with the better route.

4.3.3 Route Response

When a route reply finds its way back to the source using the information on the source route along with the extension factors to be used on the different links, it is checked by every intermediate node along the path. If the locally cached route to the source has a better route metric than that currently being used, then it replaces the portion of the route from itself to the source with the locally stored route. Thus, when the route reply finds its way back to the source, the nodes update the route in the packet with their locally cached route that is made up of minimal range links as determined by the metric. Hence, when the source finally gets back the route reply, the route contained in it consists of all rate links if such a quality route exists or with the minimal impact from range links otherwise. When a flow is considered in isolation, the worst case delay incurred by MIR in getting the request delivered to the destination is $T \cdot (l + K - 1)$ neglecting the short preambles, with $T \cdot (l - 1)$ constituted by the propagation of request until the last set of i hops and TK constituted by the worst case waiting time at the destination to allow for local bridging; $l = \frac{h}{K}$, h is assumed to be an integral multiple of K without any loss of generality. This is reasonable compared with the best case delay of Tl seconds in MUX. The route reply propagation would however incur the same latency in both cases.

MIR is thus able to obtain quality routes with the minimal impact from range links at the cost of a small additional delay. The main benefit of this mechanism is that, it does not require the routing protocol to be aware of the network density in order to be able to change strategy in determining routes but can obtain the quality routes provided by the underlying topology for any given density in a transparent fashion. Also, by helping obtain routes with high rate (predominantly rate links), it provides more potential to alleviate link breakages due to mobility and channel effects by switching to diversity techniques, which are explained subsequently.

While the sparse nature of the network is a steady-state feature of the network, mobility and channel errors are network dynamics that need to be handled by the routing protocol through its route maintenance component to avoid throughput degradation.

4.3.4 Route Failure Detection during Mobility and Channel Degradation

The challenge is to detect that a link is going to break due to mobility or persistent channel degradation. The MAC in MIR addresses this challenge by switching from MUX to diversity after four trials of the RTS packet (RTS has a maximum retry limit of seven in IEEE 802.11b). However, depending on the nature of the loss (mobility or channel degradation), the gain in SNR automatically provides increased range for a far-by receiver (DIV-RANGE), or increased reliability for a close-by receiver (DIV-BER) to appropriately recover from the loss. Hence, it is not necessary to differentiate between mobility and channel error losses which is a very useful feature. When switching to diversity, the number of elements used towards diversity is initially two, since in most cases the range extension or increased reliability resulting from a diversity order of four is easily sufficient to sustain the link from breaking even at high speeds (30 m/s) and high packet error rates (30-40%). This keeps the reduction in rate and spatial reuse (if increased communication range is exploited) due to diversity to a minimum and exploits the remaining elements to increase the rate of transmission through MUX. It also keeps the overhead due to short preambles very small. If the link is already operating in diversity, then an increase in number of elements exploited for diversity by one will still serve the purpose.

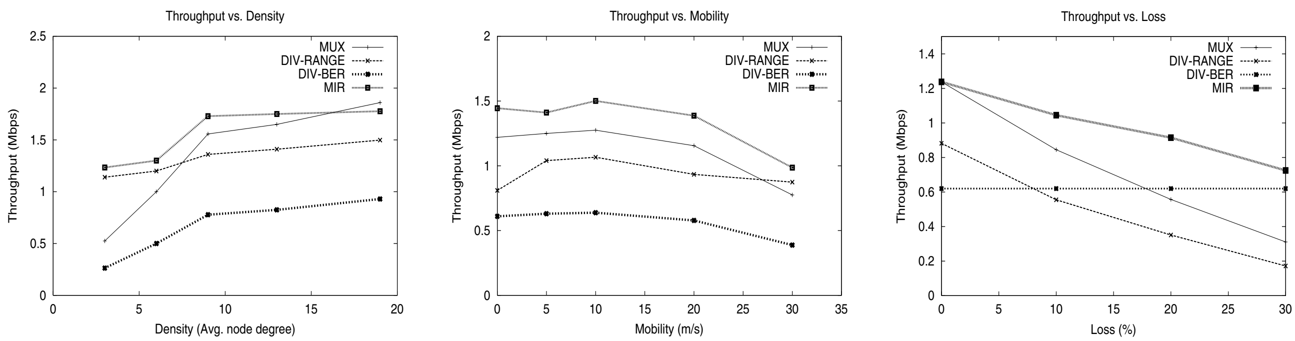
If the increased communication range or reliability due to diversity is able to get the packet across, then there are two possible cases: (i) receiver was actually moving away and/or the channel quality was bad; or (ii) neither the receiver was moving away nor the channel quality was bad. The second case is a false alarm (negative) but can be handled easily. The change of strategy is known to the receiver through the normal preamble that is always transmitted using diversity (STBC). Once the receiver receives the RTS, it sends back the CTS using the same strategy used by the transmitter. However, the transmitter on receiving back the CTS packet can determine the false alarm (assuming symmetric channel conditions) if it can successfully decode the short preamble that was transmitted using a lesser (previously used) diversity order than that used by it on its RTS. On the other hand, if the transmitter cannot decode short preambles of lower diversity orders, then a "proactive" route error can be generated confidently. However, when the extended communication range or increased reliability is also not able to get the packet across, we again have two cases: (i) neither the receiver was moving nor the channel quality was bad but there is contention; or (ii) receiver was moving and/or channel quality was bad and there is contention. In both cases, we would appropriately infer congestion and would not generate a proactive route error.

4.3.5 Route Maintenance

Once the link failure due to mobility or persistent channel errors has been "proactively" detected, the routing protocol at the node is informed. MIR at the detection node recognizes the proactive link failure and hence does not purge packets from the queue that are using the link. It generates a proactive route error to the source. The intermediate nodes delete routes from their caches (but do not purge packets) that contain the detected link as in a normal route error so that they do not respond back to the new proactive route discovery process with the stale route. Once the source receives the proactive route error, it initiates a new route request for the destination to obtain a better route with minimal impact from range links through the route discovery component. However, it does not purge the routes that contain the detected link until a new route is obtained or an official route error is received and uses the existing route for sending the packets currently in its buffer. The MAC at the node that detected the proactive route error, though it has switched to diversity to enable communication on the link, it continues to keep track of the diversity order that is supported by the link in conjunction with its receiver through the short preambles. Once it finds that the diversity order used prior to switching can be supported again by the link within four transmissions in succession, it generates a "route error cancel" notification to the source to prevent the unnecessary route change. This would automatically take care of the case wherein the receiver moves out of the current communication range and then comes back into it within a very short duration, and also the case where the channel degradation is short-term. This is because when the receiver moves back in or the channel quality becomes good, the transmitter would receive the short preamble corresponding to a lower diversity order.

When a new route is obtained, the source switches its route to the new route and purges the old routes that contain the detected link. The reaction to an official route error is the same as in a conventional source-driven reactive protocol such as DSR. Further, the granularity of the time taken for a link to break due to mobility or persistent channel errors under increased diversity is large when compared to the route discovery latency. This is because the route discovery component in MIR obtains a route in a time close to that of the high rate MUX scheme. Hence, the proactive route is obtained before the detected link actually fails. Thus, proactive switching from MUX to diversity helps reduce the number of route errors due to mobility and persistent channel errors that occur in time-correlated fading, thereby reducing the degradation in throughput, while also addressing all the challenges outlined in Section 4.1.2. Further, exploiting diversity is different in principle from the typical topology control algorithms where transmission power is used to control the communication range and increase the link reliability, since it does not require any change in transmit power, thereby not complicating the MAC protocol operation.

In summary, the components in MIR exploit multiplexing to increase the rate of a flow but intelligently use diver-



a) Density b) Mobility c) Loss (Load = 15 flows)

Figure 3. Individual Impact of Components on Aggregate Throughput

sity in their route discovery and maintenance components based on the perceived network conditions to obtain quality routes and to prevent degradation in throughput.

5 Peformance Evaluation

In this section, we evaluate the performance of MIR against MUX, DIV-RANGE and DIV-BER strategies. We evaluate the different strategies in the *ns2* simulator. The density, load, mobility and loss characteristics of the link are varied from one experiment to another. We assume the range extension function f to be linear. The constant ϕ in the route discovery component is empirically set to 5. The number of elements is fixed at two initially for fair comparisons between the different strategies since we do not want the range extension resulting from DIV-RANGE to be limited by the topology size. We also do not want the usage of additional elements for increasing reliability in DIV-BER when the existing elements themselves have reduced the link error probability to a negligible value. Later on, we do consider the impact of number of elements on the different strategies. We represent density of the network by the average node degree parameter ρ. ρ is varied from 3 (sparse networks, 100 nodes in 2500m*2500m) to as high as 19 (dense networks, 100 nodes in 1000m*1000m) with the transmission range being 250m. Mobility and link loss rates are varied upto 30 m/s and 30% respectively. The default values of load, mobility and loss rate are 30, 0 m/s and 0% unless varied or specified otherwise. Each flow uses CBR as the traffic generating application at a rate of 100 Kbps on a 2 Mbps channel with a packet size of 1 KB and UDP serving as the transport protocol. MIR is implemented by effecting the necessary changes to the DSR routing protocol, with support from IEEE 802.11b MAC protocol in DCF mode using standard specifications. In addition to the two-ray ground propagation model supported in *ns2*, we incorporate the impact of time-correlated Rayleigh fading on packet errors through a new collision model. The collision model captures the probability of packet errors for various configurations (locations and MIMO strategies used) of desired transmitters and interferers in the presence of time-correlated Rayleigh fading. This is in turn derived from the BER statistics obtained from bit-level Matlab simulations of detailed physical layer modeling of spatial multiplexing and diversity in the presence of Rayleigh fading with time correlation. The scenarios are generated using the random waypoint mobility model. Aggregate throughput is the primary metric of comparison and each of the data point in the results presented is averaged over 10 seeds with each seed running for 100s.

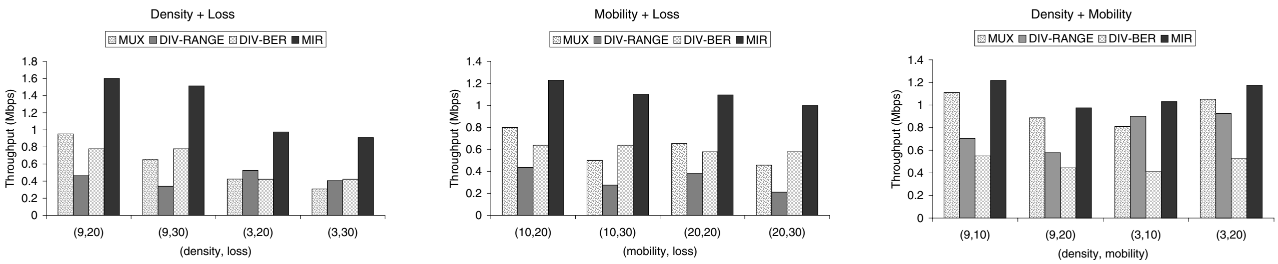
5.1 Individual impact of components

5.1.1 Varying density

Figure 3(a) presents the aggregate throughput results for the different strategies as a function of node density (average node degree) for a load of 30 flows. No mobility of nodes or losses on the links are considered. It can be seen that irrespective of the density, MIR is able to track the performance of the best strategy, which is DIV-RANGE in the sparse network case and MUX in the dense network case.

5.1.2 Varying mobility

In these experiments, the load in the network is maintained at 15 flows and the links are assumed to be almost non-lossy. The mobility is varied till 30m/s and the results are presented in Figure 3(b). Recall that, DIV-RANGE is outperformed by MUX at lower speeds due to the increased contention experienced from extended range that outweighs its robustness to mobility. MIR delivers the best performance since it emulates the MUX scheme while at the same time increases robustness by reducing the number of route errors experienced by an intelligent use of diversity.



a) Density + Loss (No mobility) b) Mobility + Loss (density = 19) c) Density + Mobility (No loss)

Figure 4. Combined Impact of Components

5.1.3 Varying loss characteristics

The loss rates on the links are varied in this set of experiments from 0% to 30%. The nodes are assumed to be static and the network size considered is a dense environment with 100 nodes in 1000m*1000m. Figure 3(c) presents the result where aggregate throughput is recorded as a function of loss percentage for a load of 15 flows. MUX is able to outperform DIV-BER only at low error rates ($<$ 15%) since the degradation due to losses in MUX is not significant when compared to the rate that is sacrificed in DIV-BER. DIV-RANGE not only suffers from reduced rate as in DIV-BER, but also from the decreased link reliability due to longer links, thereby exhibiting poor performance. In both these cases, MIR is able to adapt MUX to incorporate DIV-BER, thereby increasing the robustness of the link based on the link conditions and is hence able to deliver performance improvement.

5.2 Joint impact of components

In the following experiments the load in the network is fixed at 15 flows, each flow having a rate of 100 Kbps.

5.2.1 Density + loss

We now evaluate the joint performance gains of the route discovery and link error components in MIR. We assume static nodes but consider densities of 3 and 9 and loss rates of 20% and 30% in four possible combinations. The results for the different schemes are presented in Figure 4(a). First let us consider MUX, DIV-BER and DIV-RANGE alone for comparison. At higher densities and lower loss rates, MUX performs the best while DIV-BER suffers from reduced rate and DIV-RANGE suffers from reduced rate as well as reduced spatial reuse. However, at higher loss rates (30%), DIV-BER performs the best. DIV-RANGE exhibits the best performance in lower densities and lower loss rates. In the case of lower densities but higher loss rates, the choice could be between DIV-BER and DIV-RANGE depending on how the benefits of increased range and increased reliability outweigh the respective drawbacks in the two cases. Finally, MIR incorporates the advantages of MUX at lower loss rates and higher densities, the advantages of DIV-BER at higher loss rates and the benefits of DIV-RANGE at lower network densities in a transparent manner to provide significant gains of about 100%.

5.2.2 Mobility + loss

Figure 4(b) presents the performance gains of the mobility and link error components of the different strategies. Considering MUX, DIV-BER and DIV-RANGE alone initially, it can be seen that MUX provides higher gains than the other two strategies for lower speeds and lower loss rates. At higher loss rates, as expected DIV-BER delivers better performance. However, the magnitude of gain is decreased. This is because link (channel) errors which might be recovered by DIV-BER in the static case, might well be lost in the combined presence of mobility and channel errors. The benefit of DIV-RANGE in mobile scenarios appears only at large speeds close to 30 m/s. For the scenarios considered here, the increased communication range (increased contention) and loss, and reduced rate and spatial reuse in DIV-RANGE all contribute to its worst performance. Finally, MIR combines the benefits of increased reliability (DIV-BER) for handling link errors and increased range (DIV-RANGE) for handling mobility gracefully, with MUX serving as its base strategy of operation to provide gains close to 100%.

5.2.3 Density + mobility

Figure 4(c) presents the results for the joint performance of the route discovery and mobility components in MIR. It can be seen that MUX performs better than DIV-RANGE for higher densities. The robustness of DIV-RANGE to mobility over MUX does not contribute much when compared to the reduction in spatial reuse and rate at higher densities. While DIV-RANGE does perform better than MUX at lower densities and low mobility, it is interesting to note that MUX performs better than DIV-RANGE at lower densities of $\rho = 3$ in the presence of high mobility. This can be explained as follows. It can be seen from the result that increasing mobility from 10m/s to 20m/s actually helps MUX obtain better performance at low density. This is possibly due to the fact that flows that have no routes in static (or low mobility) sparse network condition, may be able to form routes due to high mobility. Hence, the benefit of DIV-RANGE to be able to form routes that do not exist in MUX is decreased. Furthermore, the gain of MIR over MUX is also only moderate. We would have expected MIR to track the performance of MUX or DIV-RANGE depending on the density and also provide the benefits of diversity for handling mobility. But as pointed out before, mobility has not degraded MUX's performance significantly. In fact it has aided MUX at lower densities. Hence, the gain of the mobility and route discovery components in MIR is decreased in this case. However, the gain is still more than 25%.

6 Related Work

There have been several works that have looked at the problem of medium access control [8, 10, 3, 7] and routing protocols [9, 2] in ad-hoc networks in the presence of switched beam antennas. While the list is by no means complete, the amount of work in the context of adaptive arrays and MIMO links has been relatively scarce from the networking perspective, given the default acceptance of MIMO in several upcoming standards. Recently, [12] has specifically looked at the design of MAC protocol for ad-hoc networks with MIMO links. To the best of our knowledge, our work is the first to consider the problem of routing in ad-hoc networks with MIMO links. While there have been several ad-hoc routing works that have looked at the problems of mobility, partitions, etc., in omni-directional environments, our focus here is to approach these problems from the perspective of exploiting a more sophisticated PHY layer antenna technology.

7 Conclusions

In this work, we have outlined the different strategies for operation with MIMO links in ad-hoc networks, and identified their relevance to the performance improvement of routing layer protocols. Specifically, we have identified the relative merits and de-merits of the different strategies under different network conditions. Using the insights gained from the study, an adaptive routing protocol called *MIR* has been proposed that adapts between the different strategies based on the network conditions. The effectiveness of the proposed protocol has been evaluated using *ns2* simulations. We intend to address some of the security issues that arise from the proposed routing mechanisms as well as investigate the objective of power minimization as part of our future work.

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