Exploiting Cooperative Relay for High Performance Communications in MIMO Ad Hoc Networks

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Abstract—With the popularity of wireless devices and the increase of computing and storage resources, there are increasing interests in supporting mobile computing techniques. Particularly, ad hoc networks can potentially connect different wireless devices to enable more powerful wireless applications and mobile computing capabilities. To meet the ever increasing communication need, it is important to improve the network throughput while guaranteeing transmission reliability. Multiple-input-multiple-output (MIMO) technology can provide significantly higher data rate in ad hoc networks where nodes are equipped with multi-antenna arrays. Although MIMO technique itself can support diversity transmission when channel condition degrades, the use of diversity transmission often compromises the multiplexing gain and is also not enough to deal with extremely weak channel. Instead, in this work, we exploit the use of cooperative relay transmission (which is often used in a single antenna environment to improve reliability) in a MIMO-based ad hoc network to cope with harsh channel condition. We design both centralized and distributed scheduling algorithms to support adaptive use of cooperative relay transmission when the direct transmission cannot be successfully performed. Our algorithm effectively exploits the cooperative multiplexing gain and cooperative diversity gain to achieve higher data rate and higher reliability under various channel conditions. Our scheduling scheme can efficiently invoke relay transmission without introducing significant signaling overhead as conventional relay schemes, and seamlessly integrate relay transmission with multiplexed MIMO transmission. We also design a MAC protocol to implement the distributed algorithm. Our performance results demonstrate that the use of cooperative relay in a MIMO framework could bring in a significant throughput improvement in all the scenarios studied, with the variation of node density, link failure ratio, packet arrival rate and retransmission threshold.

Index Terms—MIMO, relay, scheduling, ad hoc networks, cooperative.

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1 INTRODUCTION

THere are increasing interests and use of mobile ad hoc networks with the proliferation of mobile, network-enabled wireless devices, and the fast progress of computing techniques and wireless networking techniques. In a mobile ad-hoc network (MANET), wireless devices could self-configure and form a network with an arbitrary topology. The network's topology may change rapidly and unpredictably. Such a network may operate in a stand-alone fashion, or may be connected to the larger Internet. Mobile ad-hoc networks became a popular subject for research in recent years, and various studies have been made to increase the performance of ad hoc networks and support more advanced mobile computing and applications [1]–[4].

As the number, CPU power and storage space of wireless devices continue to grow, there is a significant increase in data transmission demand to support data intensive mobile computing and applications, such as multimedia streaming, gaming, transmission of a large amount of event data during environmental monitoring, and distributed and collaborative processing among a set of wireless devices. To meet the high data rate requirements, a surge of interest in multiple-input multiple-output (MIMO) technology is observed in the past a few years. A MIMO system could potentially improve the transmission reliability and provide higher raw data rates by utilizing multiple antennas at the transmitter and/or the receiver. Specifically, *multiplexing* takes advantage of the rich scattering environment to increase the transmission capacity [5] and *diversity* effectively combats fading to enhance the transmission reliability [6], [7]. In order to exploit the benefits of MIMO technology, it is now being adopted in 802.11n [8] and also considered for ad hoc networks.

Some recent works have endeavored to apply MIMO techniques in ad hoc networks [9]–[18]. Although various MAC schemes have been designed to exploit the intrinsic features of MIMO to improve the throughput and reliability, they may not be able to handle consecutive packet loss due to severe path loss, continuous deep fading or temporary topology changes and link breakages. Continuous packet retransmissions would lead to significant throughout reduction. The severe transmission conditions pose a big threat to the growth of wireless applications. Although beamforming can help improve the transmission reliability, it compromises the potential multiplexing gain and hence reduces the transmission rate. In addition, when the channel condition is extremely weak or the distance between the transmitter and receiver is temporarily very long, even beaming-forming may not be able to ensure the transmission reliability for the direct link. Moreover,

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the design of MAC scheme to coordinate beamforming transmissions in a multi-hop network is very difficult. As an alternative to MIMO technique, recent efforts have been made to enable cooperative relay transmission to cope with channel degradation, with the assumption that network nodes have single antenna [19]–[21]. One question to raise is: is it beneficial to adopt cooperative relay to facilitate transmission in a MIMO-based ad hoc network?

The introduction of cooperative relay transmission into a network where nodes are equipped with multiple antennas could bring in benefits far beyond that of simply combining the two techniques together. It would not only allow joint exploitation of multiplexing gain of MIMO and cooperative diversity gain of relay transmission, but would also help mitigate many issues presenting in conventional relay transmissions. First, with the support of relay nodes, transmissions on MIMO links with harsh conditions or temporary breakages can possibly be bridged through relay links over source-relay-destination paths. Without being impacted by a poor link for a continuous time period, traffic can be scheduled more efficiently to avoid a significant transmission delay and extra consumption of precious network resources. Second, with a careful relay selection, the channel quality of a relay link would be generally better thus allow for a higher rate, which reduces the cost of using relay transmission. Third, taking advantage of multi-packet transmission/reception capability enabled by MIMO technique, a relay node which has multiple antennas can overhear the transmission from a source while receiving its own packets, which avoids the need for the source to forward the packet explicitly to the relay node as in conventional cooperative transmission. Meanwhile, a relay node can simultaneously forward packet for others while transmitting its own packets.

Although the benefits of using relay transmission in a MIMO ad hoc network are significant, there are also big challenges in efficiently selecting and triggering cooperative relay transmissions, especially in concert with multi-user-based MIMO transmissions in an ad hoc network environment. Without a properly designed strategy, the use of relay would cost much more transmission time and bandwidth instead of supplementing the spatial multiplexing transmission.

In this paper, our focus is to design algorithms along with a MAC scheme that *opportunistically* use cooperative relay in MIMO-based ad hoc networks to further improve the transmission reliability and throughput when the transmissions between two nodes encounter difficulty. Our proposed strategy is named as Cooperative Relayed Spatial Multiplexing (CRSM). The main contributions of this paper are as follows.

- We mathematically model the problem and provide a centralized algorithm with proved approximation ratio to serve as the performance reference of the distributed algorithm;
- We practically divide the problem into two phases and provide simple but effective distributed scheduling algorithms that seamlessly incorporate the use of cooperative relay into MIMO transmission, which can guide the practical protocol design;
- We propose a simple relay scheme to formulate relay set and invoke relay transmission without extra signaling overhead;
- We design an efficient MAC protocol to support our distributed algorithm.

The rest of the paper is organized as follows. We introduce the motivation of our work in Section 2. We formulate the problem and propose a centralized algorithm with proved approximation ratio in Section 3. We then present our scheduling algorithms to support seamless use of cooperative relay with multi-user-based MIMO transmission in an ad hoc network in Section 4, and provide more details about relay operation and MAC protocol design in Section 5. The performance of the proposed algorithms is studied through simulations in Section 6. Finally, we discuss the related work in Section 7 and conclude the paper in Section 8.

2 BACKGROUND AND MOTIVATION

In an ad hoc network where nodes are equipped with multiple antennas, there are generally two types of gain achieved by MIMO transmission. *Multiplexing gain* refers to the increase in raw data rate by concurrent transmission of multiple data streams between a node pair, and *diversity gain* is achieved by space time coding or antenna selection which may be exploited to improve the transmission reliability. In this work, we make an effort to leverage the multiplexing gain and diversity gain brought by MIMO transmission along with multi user diversity in a network with mesh topology. Instead of only allowing multiplexed transmission between a pair of nodes as in traditional MIMO scheme, we consider cooperative MIMO multiplexed transmission in which multiple nodes can simultaneously transmit to a receiver that has multiple antennas, i.e. forming a virtual MIMO array [22], and a sender with multiple antennas can also transmit multiple streams to a set of nodes. In this way, many-to-many transmissions are allowed between node pairs to better exploit multiplexing gain. Moreover, among the transmission links between node pairs, those whose channel qualities are higher can be selected for transmission to exploit multiuser diversity gain. When the information of channel coefficients is available for a node pair, a subset of antennas that transmit signals at better quality can be opportunistically selected for transmissions, such a scheme takes advantage of selection diversity and is shown to outperform space-time coding [23]. This framework, named Opportunistic and Cooperative Spatial Multiplexing (OCSM), is illustrated in Fig. 1. Empowered with the opportunistic and cooperative transmission capability, node 3 transmits to node 2 and 4 simultaneously with selected antennas, and node 2 is able to receives two data streams from node 1 and one data stream as well as one interference stream from node 3.

The OCSM framework allows the exploration of multiuser diversity and antenna selection diversity to further improve the capacity and reliability of the network [17]. These diversity techniques, however, are insufficient when the channel condition is extremely weak, the existence of correlated fading between a sender and receiver pair,

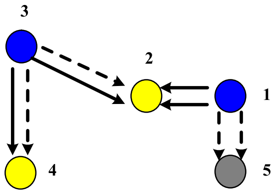

Fig. 1. An illustration of Opportunistic and Cooperative Spatial Multiplexing (OCSM).

or the distance between a node pair changes as a result of temporary topology change. If the channel degradation is short-term, it would be inefficient to change the transmission path immediately. Although schemes such as beamforming could be used between the transmission pair which has severe channel condition, it may prevent concurrent transmissions from the same or other nodes and compromise the potential throughput gain of the network that could be achieved with multiplexed transmissions. Also, sometimes even beamforming is hard to handle a weak transmission between two nodes when their distance is large enough or the channel is very weak, although the two nodes are within two-hop transmission distance.

In order to alleviate the problem of data rate reduction and excessive queuing delay caused by severe channel condition and/or link breakage as a result of temporary network topology change, in this work, we propose to adaptively invoke *cooperative relay* in conjunction with *cooperative multiplexing MIMO communications* when direct transmission cannot be successfully pursued. There are some unique benefits by taking advantage of both techniques.

- *Concurrently exploiting cooperative diversity and spatial multiplexing for transmission robustness and higher throughput.* Different from the literature work which exploits cooperative diversity in a single antenna case only to improve the transmission quality, in the proposed work, the relay transmissions coordinate with the transmissions in a neighborhood and take advantage of *cooperative multiplexing* to improve the overall network throughput.
- *Obtaining relay packets without extra overhead.* With multi-packet reception capability brought by multiple antennas, a relay node can obtain the packet to be relayed through overhearing during its own data receiving when the sender attempts for initial direct transmission. As an example, in Fig. 2(a), R receives the relay packet as an interference stream while it is receiving data stream from Q. Assume R has 2 antennas, it is therefore able to decode the packet from Q as well as the relay packets from S.
- *Relay packet forwarding in conjunction with normal packet transmissions.* Instead of simply postponing the transmissions of packets with relay nodes as the direct sender, which is often the case in the conventional cooperative diversity study, a relay node can transmit a relay packet concurrently with its own packets, therefore avoid excessive delay for its own packets. As shown in Fig. 2(b), node R can simultaneously transmit to Q when it serves as a relay node to transmit the relay packet to D. A relay node can even have a higher transmission probability driven by our priority based scheduling, as the priority of a relay node increases when its packets experience longer delay due to relay transmissions.
- *Relaxed synchronization requirements taking advantage of multi-stream reception capability of receivers.* The direct transmissions and relayed transmissions are performed independently, and a receiver node takes advantage of multiple antennas to decode transmissions from multiple streams without requiring synchronization at the symbol level between neighboring nodes as in conventional cooperative diversity schemes.

With use of coded cooperation, the network performance can be further improved. As our focus is to investigate the benefit and strategy of incorporating relay into multiplexed MIMO transmission, we consider decode and forward cooperative strategy here for simplicity.

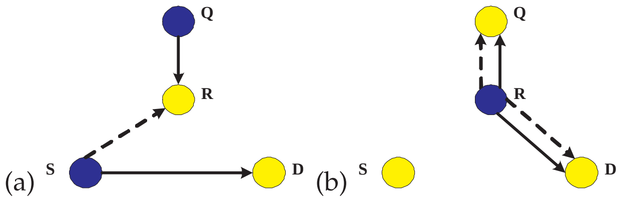

Fig. 2. An illustration of cooperative relay transmission.

3 PROBLEM FORMULATION AND A CENTRALIZED SOLUTION

In this section, we first describe the system model and introduce some notations to use in the paper. We then provide a mathematical formulation of the problem to guide the design of scheduling algorithms. The modeling of transmission opportunities and constraints to enable cooperative MIMO transmissions in multi hop wireless mesh network involves a big challenge, while the need of incorporating relay transmissions makes the problem even harder. Finally, we provide a centralized algorithm with provable approximation ratio to serve as the performance reference of the distributed algorithm to be introduced in the next section.

3.1 Problem Formulation

To enable concurrent many-to-many stream transmission, our MAC design is TDMA-based, in which the time domain is divided into transmission durations (TD). A TD covers one round of control signal exchange and data frame transmission and consists of a fixed sequence of phases each with a fixed length. Channel conditions are supposed to be quasi-static during a TD. The data transmission rate within a TD can vary for different links based on the their channel conditions, i.e. more efficient coding can be used to encode the symbols at a higher rate for a channel with higher quality. As the total transmit power of each node is generally fixed, the transmit power of each antenna is different when a node uses a different number of antennas for transmission.

As the complete information about future traffic is unavailable, it is a practical option to schedule the transmission of packets in each TD considering the existing

TABLE 1
LIST OF NOTATIONS USED IN PROBLEM FORMULATION.

Notation	Definition
$i = 1, \ldots, N_p$	Index of packets
$j = 1, \ldots, N_n$	Index of nodes
$h_j \in \{0, 1\}$	$h_j = 1$ if and only if node j is selected as a receiver
$t_j \in \{0, 1\}$	$t_j = 1$ if and only if node j is selected as a transmitter
$y_{ij} \in \{0, 1\}$	$y_{ij} = 1$ if and only if packet i is assigned to be transmitted from node j
$a_{ijk} \in \{0, 1\}$	$a_{ijk} = 1$ if and only if packet i is assigned to be transmitted from the k-th antenna of node j
$s = (I_t, I_r, I_{ant})$	Stream from the I_{ant}-th antenna of transmitter I_t to receiver I_r
R_i	The set of candidate relay nodes for packet i
$\mathscr{P}(i)$	Priority of packet i
$\mathscr{R}(s)$	Data rate of stream s
$\mathscr{I}(d_i)$	Interference at receiver node d_i when receiving packet i

traffic and queueing delay, and the scheduling scheme is consecutively executed during the lifetime of the network. In a TD, suppose there is a set of N_n nodes $N = \{1, 2, \ldots, N_n\}$ in the network, and there are N_p packets waiting for transmission which are contained in the set $P_{pkt} = \{1, 2, \ldots, N_p\}$. A node j has an antenna array of size N_j^{ant}. There is a buffer queue at each node where data packets are stored. For a packet i, a parameter called *priority* $\mathscr{P}(i)$ is used to capture both its service type and queuing delay. For the convenience of calculation, $\mathscr{P}(i)$ is measured in the unit of TD. A possible way to integrate both factors into the priority calculation is to equate the service priority of i to an initial value of $\mathscr{P}(i)$ in terms of TD, and $\mathscr{P}(i)$ increases as the queuing time of p_i increases. A higher value of $\mathscr{P}(i)$ indicates that the packet i has a higher priority.

The transmissions of packets are organized as *streams*. For spatial multiplexed transmission, a stream s is defined to be an independent data flow transmitted from an antenna of a transmitter node to a receiver node and identified by a triplet $s = (I_t, I_r, I_{ant})$, where $I_t/I_r/I_{ant}$ is the index of the transmitter/receiver/antenna that involves in the transmission of the stream. Suppose the signal to noise and interference ratio (SINR) at the receiver node is $\rho_{I_r}(s)$ for stream s, the data rate of s can be calculated as $\mathscr{R}(s) = \log(1 + \rho_{I_r}(s))$. In a practical system, a receiver can include its estimated $\rho_{I_r}(s)$ in its feedback message, and a transmitter can then decide the actual data rate based on the SINR information, i.e. by looking up a pre-set table. The transmissions in the network are half-duplex, so a node cannot be a transmitter and receiver at the same time. In a TD, a subset of nodes, denoted as T, are selected as transmitter nodes.

The notations used in the problem formulation are summarized in Table 1. Denote the set of neighboring nodes of node j as $\mathscr{V}_j$. Suppose the transmission of a packet i is through stream $s(i)$, and the reception is successful when the receiving SINR $\rho_{I_r}(s(i))$ is above a certain threshold Γ. After a direct transmission of a packet i from s_i to d_i, nodes that successfully overhear the packet while are in the transmission range of s_i and the receiving range of d_i, i.e. those in the set $R_i = \{r | \forall r \in N \setminus T, s.t.\ s_i \in \mathscr{V}_r, d_i \in \mathscr{V}_r, \rho_{I_r}(s(i)) \geq \Gamma\}$, store the packet in their own buffers. These nodes become candidate relay nodes for packet i. The packet i becomes available to nodes in $R_i \bigcup \{s_i\}$, which store the packet with the consistent priority. R_i is updated to include more qualified relay nodes whenever there is any direct transmission of i. When $y_{ij} = 1$, it implicitly indicates that $j \in R_i \bigcup \{s_i\}$.

Note that if $a_{ijk} = 1$, the transmission rate of packet i depends on the channel condition of the stream $s(i) = (j, d_i, k)$ and the interference at node d_i when receiving the stream, denoted as $\mathscr{I}(d_i)$. Therefore, the rate of stream $s(i)$ is denoted as $\mathscr{R}(s(i), \mathscr{I}(d_i))$.

We now can formulate the constraints for the problem of cooperative relayed spatial multiplexing in a MIMO ad hoc network to capture the features of MIMO transmissions and conditions of relay transmissions. Firstly, it is necessary to ensure that a packet i is assigned to at most one transmitter node among all the candidate ones (including the source node s_i and candidate relay nodes in R_i) to avoid redundant transmission,

$$\sum_{j \in R_i \bigcup \{s_i\}} y_{ij} \leq 1, i \in P_{pkt}. \tag{1}$$

As the *transmitting constraint*, an antenna k at a transmitter j can only accommodate the transmission of at most one stream in a TD,

$$\sum_{i \in P_{pkt}} a_{ijk} \leq 1 + (1 - t_j)M, j \in N, k = 1, \ldots, N_j^{ant}; \tag{2}$$

where M is a sufficiently large number introduced to relax the constraint when node j is not selected as the transmitter, i.e., $t_j = 0$. Similarly, the *receiving constraint* is used to model the impact of interference at the receiver end of a MIMO link, where the total number of receiving streams (data streams plus interference streams) at a receiver node j is restricted to be no more than its number of antennas in order to decode the receiving data packet,

$$\sum_{i \in P_{pkt}} \sum_{m \in \mathscr{V}_j} \sum_{k=1}^{N_m^{ant}} a_{imk} \leq N_j^{ant} + (1 - h_j)M, j \in N. \tag{3}$$

To ensure that the transmission is half-duplex, t_j and h_j for each j have to satisfy

$$t_j + h_j \leq 1, j \in N. \tag{4}$$

It is also important to constrain the relation between the parameters,

$$\begin{aligned} &a_{ijk} \leq y_{ij} \leq t_j, a_{ijk} \leq y_{ij} \leq h_{d_i}, \\ &i \in P_{pkt}, j \in N, k = 1, \ldots, N_j^{ant}. \end{aligned} \tag{5}$$

Finally, following the scheduling framework in [24], our scheduling aims to maximize the sum of priority-weighted capacity so that both data rate and priority can be jointly optimized. The objective function is:

$$\max \sum_{i \in P_{pkt}} \sum_{j \in R_i \bigcup \{s_i\}} \sum_{k=1}^{N_j^{ant}} a_{ijk} \mathscr{R}(s(i), \mathscr{I}(d_i)) \mathscr{P}(i). \tag{6}$$

With this formulation, the nodes without packets will have the priority set to 0 and not be scheduled to transmit, while the packets associated with worse quality links will still get chance to transmit as their priority increases.

So far, we formulate the problem of cooperative transmission with relays in a MIMO ad hoc network as an integer linear programming (ILP) problem with objective function in (6) subject to constraints (1)(2)(3)(4)(5). As an ILP problem is NP-hard in general and needs exponential time complexity to find a solution, an efficient heuristic algorithm is required for the practical implementation.

3.2 A Centralized Algorithm

In Algorithm 1, we propose a centralized scheme to schedule packet transmissions in a single TD. As the interference streams which can transmit simultaneously with stream i are unknown before the scheduling is finalized, it makes the accurate determination of $\mathscr{R}(s(i), \mathscr{I}(d_i))$ difficult. On the other hand, as the transmission rate is only used as a guidance to select the streams that potentially support higher throughput for transmissions, it is not necessary to know the accurate transmission rate at scheduling time. Therefore, we consider the maximum possible receiving interference and use it for the conservative estimation of rate for each candidate stream. Specifically, as the number of interference and data stream could not exceed $N_{d_i}^{ant}$ for correct decoding, $N_{d_i}^{ant} - 1$ strongest candidate streams around d_i are considered to calculate the interference strength. The estimated value of $\mathscr{R}(s(i), \mathscr{I}(d_i))$ is then calculated based on the channel condition of the stream and the interference strength, and is then used in the centralized algorithm. Note that our algorithm does not prevent using other model for stream rate determination. When channel conditions from all the potential transmitters are estimated in advance, more sophisticated techniques could be used to cancel the majority of interference, and thus further improve the transmission rate.

The algorithm is to be executed by a central controller of the network which has the complete information of packets and channels. To facilitate scheduling, a parameter $w(ijk)$ is introduced to represent the priority weighted data rate achieved with the transmission of packet i from transmitter j using antenna k as in (6), and the set W consists of the weighted rates of all candidate streams, as in lines 2-7. The algorithm greedily schedules a packet i^* to transmit from antenna k^* of transmitter node j^*, which has the highest weighted rate among all the candidate ones and guarantees the constraints (2)-(3). P is the set of scheduled packets and T contains all selected transmitters. In line 12, all the candidate streams that have transmission conflict with the scheduled stream $s = (j^*, d_{i^*}, k^*)$ are removed from the set W, including the ones that have the node j^* as the receiver, have d_{i^*} as the transmitter, or have node j^* as the transmitter but are associated with the antenna k^*. A packet may be queued at multiple candidate transmitting nodes, i.e. source and candidate relay nodes. To avoid repetitive transmission of a packet and satisfy constraint (1), all other candidate streams for the selected packet i^* are also removed from W after i^* is successfully scheduled in the current TD. The algorithm then checks if packets are correctly received at destinations in lines 18-19, and successfully received packets are removed from the packet set P_{pkt}. For any incorrectly received packet i, its candidate relay list R_i is updated to add in nodes that are within the range of both the source and destination of i and have correctly overheard the direct transmission, as i n lines 21-23, so that nodes in R_i would assist in the transmission of i in the following TDs.

The numbers of cycles for the Initialization phase from line 0 to 7 and the Relay Set Update phase from line 17 to 27 are both in $O(N_p N_n)$. In the Scheduling phase from line 8 to 16, at least one candidate stream is removed from set W in each iteration. As the size of antenna array is a constant for each node, the number of candidate streams between each node pair does not exceed a constant $A = \{\max_i\{N_i^{ant}\}\}^2$, and there are thus no more than $A(N_n)^2$ candidate streams in W. Suppose the elements in the set W are sorted in descending order by their values, and it requires $O(N_n)$ to suppress streams in line 12. Therefore, the complexity of the algorithm is $O((N_n)^3)$.

Algorithm 1 Centralized Scheduling

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 0: Initialization:
 1: $W \Leftarrow \oslash$, $T \Leftarrow \oslash$, $P \Leftarrow \oslash$, $y_i \Leftarrow 0$, $x_j \Leftarrow 0$, $a_{ijk} \Leftarrow 0$, $\forall i, j, k$,
    update $P_{pkt}$ to include new packets
 2: for $\forall i \in P_{pkt}$ do
 3:     for $\forall j \in R_i \bigcup \{s_i\}$ do
 4:         $w(ijk) \Leftarrow \mathscr{R}(s(i), \mathscr{I}(d_i))\mathscr{P}(i), \forall k \in \{1, \ldots, N_j^{ant}\}$
 5:         $W \Leftarrow W \bigcup \{w(ijk)\}$
 6:     end for
 7: end for
    Scheduling:
 8: while $W \neq \oslash$ do
 9:     $(i^*, j^*, k^*) = \arg\max_{\{i,j,k\}} W$, the corresponding destination node is $d_{i^*}$
10:     if Selecting stream $(j^*, d_{i^*}, k^*)$ satisfies (2) for $j^*$ and (3) for all nodes in $\mathscr{V}_{j^*}$ then
11:         Schedule the stream $(j^*, d_{i^*}, k^*)$, $y_{i^*} \Leftarrow 1$, $x_{j^*} \Leftarrow 1$,
            $a_{i^*j^*k^*} \Leftarrow 1$, $P \Leftarrow P \bigcup \{i^*\}$, $T \Leftarrow T \bigcup \{j^*\}$
12:         $W \Leftarrow W \backslash$
            $\{w(ijk) | \forall i \; s.t. d_i = j^*, \forall j \in R_i \bigcup \{s_i\}, \forall k\} \bigcup$
            $\{w(ijk) | \forall i, j = d_{i^*}, \forall k\} \bigcup$
            $\{w(ijk) | j = j^*, k = k^*, \forall i\} \bigcup$
            $\{w(ijk) | i = i^*, \forall j \in R_{i^*} \bigcup \{s_{i^*}\}, \forall k\}$
13:     else
14:         $W \Leftarrow W \setminus w(i^*j^*k^*)$
15:     end if
16: end while
    Relay Set Update:
17: for $\forall i \in P$ do
18:     if $i$ is correctly decoded at $d_i$ then
19:         $P_{pkt} \Leftarrow P_{pkt} \setminus \{i\}$
20:     else
21:         for $\forall m \in \{r | r \in \mathscr{V}_{s_i} \bigcap \mathscr{V}_{d_i}, \sum_k a_{is_ik} \geq 1, r \in N \setminus T\}$ do
22:             if $i$ is correctly decoded at $m$ then
23:                 $R_i \Leftarrow R_i \bigcup \{m\}$
24:             end if
25:         end for
26:     end if
27: end for
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Proposition: The centralized scheduling algorithm can achieve an approximation ratio of $1/\left((2 + \mathcal{D}) \max_i\{N_i^{ant}\} + 2\right)$, where $\mathcal{D}$ is the maximum node degree in the network.

Proof: Let *sol* be our solution, and *opt* be the optimum solution that achieves equation (6) while satisfying constraints (1)-(5). As shown above, in *sol*, some of the candidate streams are suppressed by the selection of a stream s (i.e., removed from W without scheduling) due to their conflicting with transmission of s but these streams may be selected for transmission in *opt* due to different selection sequence which may allow a higher total system benefit. Let $\max_i\{N_i^{ant}\}$ be the maximum antenna array size of nodes in the network. According to the constraints (2)-(5), the selection of the specific antenna k^* suppresses one stream as any other stream cannot be transmitted from k^*, the selection of the transmitter node j^* suppresses $N_{j^*}^{ant}$ streams as j^* can no longer be scheduled as a receiver node, and the selection of the receiver node $d(s_{i^*})$ suppresses $N_{d(s_{i^*})}^{ant}$ streams as $d(s_{i^*})$ can not be a transmitter node in the current TD. The sum of suppressed streams in the three cases has the upper bound $2\max_i\{N_i^{ant}\}+1$, as both $N_{j^*}^{ant}$ and $N_{d(s_{i^*})}^{ant}$ have values no larger than $\max_i\{N_i^{ant}\}$. Moreover, the assignment of transmitter/receiver eliminates their opportunity of being an idle node, while an idle node does not constrain the number of streams it perceives in the neighborhood. Denote the maximum node degree in the network as $\mathcal{D}$, the number of suppressed streams due to this reason should be no more than $\mathcal{D}\max_i\{N_i^{ant}\}$. Therefore, the number of suppressed streams that may be transmitted in one TD should be no more than $(2+\mathcal{D})\max_i\{N_i^{ant}\}+1$.

A stream $s' \in$*opt* is considered to be associated with a stream $s'' \in$*sol* either because they are identical or because s' is suppressed by s'' during the process of greedy selection. For each stream s_l in *sol*, there is a set Π_l containing the streams in *opt* that are associated with it, and $\bigcup_{s_l \in sol} \Pi_l = opt$. The number of streams in Π_l, $|\Pi_l|$, has an upper limit $(2+\mathcal{D})\max_i\{N_i^{ant}\}+2$. As the selection of stream in *sol* is greedy and searches for the one with the largest priority weighted rate at a time, thus $w(s_l) \geq w(s_m), \forall s_m \in \Pi_l$. Let U be the achieved objective function as in equation (6), we have:

$$\frac{U(sol)}{U(opt)} = \frac{\sum_{s_l \in sol} w(s_l)}{\sum_{s_l \in opt} w(s_l)} = \frac{\sum_{s_l \in sol} w(s_l)}{\sum_{s_l \in sol} \sum_{s_m \in \Pi_l} w(s_m)}$$

$$\geq \frac{\sum_{l \in sol} w(s_l)}{\sum_{s_l \in sol} \sum_{s_m \in \Pi_l} w(s_l)} = \frac{\sum_{l \in sol} w(s_l)}{\sum_{s_l \in sol} |\Pi_l| w(s_l)}$$
$$\geq \frac{\sum_{l \in sol} w(s_l)}{((2+\mathcal{D})\max_i\{N_i^{ant}\}+2)\sum_{l \in sol} w(s_l)}$$
$$= \frac{1}{(2+\mathcal{D})\max_i\{N_i^{ant}\}+2}.\square$$

Note that the approximation ratio represents the worst case that can be achieved for the centralized algorithm and is rather conservative. In general, there are not many idle nodes in the network and nodes are either transmitters or receivers, especially when many-to-many communication is enabled. In that case, it is unnecessary to consider the suppression of a potential idle node when a stream is selected, and the approximation ratio can be improved to $1/(2\max_i\{N_i^{ant}\}+2)$ when all the nodes are active transmitter or receivers.

4 PACKET SCHEDULING WITH RELAY TRANSMISSION

In order to achieve the optimum system performance, it is essential for a scheduling scheme to determine the set of nodes that serve as the transmitters and the packets to be transmitted in a transmission duration, and assign them to the appropriate antennas for transmissions. The coordination among nodes and the selection of antennas to complete these procedures in a distributed manner are highly nontrivial. The need of invoking relay transmissions upon severe channel conditions adds in significantly more challenges. In this section, we design a distributed scheduling algorithm to fully exploit the multiplexing gain enabled by cooperative MIMO transmission and diversity gain enabled by cooperative relay transmission for overall higher system performance. Specifically, our scheduling has the following features for relay handling.

- *Simple formulation of a candidate relay set for a packet.* The nodes in a neighborhood collaboratively determine if a relay transmission is needed without sophisticated signaling.
- *Simple priority-based relay selection without extra signaling.* A candidate relay node schedules the transmissions of relay packets with its own packets based on their relevant priorities. As the relevant priority of relay packets to existing packets in different candidate relay nodes are different, our scheduling naturally selects the relay transmission among a group of candidate relay nodes.
- *Support of load balancing and reduction of delay impact on relay nodes.* By incorporating delay into priority in our scheduling, a packet that experiences a longer delay as a result of repeated transmission failures of its source node has its priority increased, which may be higher than some packets at a candidate relay node (especially when the relay node has a lower load). It is therefore more likely for a relay node with lower traffic to forward the relay packets, which would balance the load of nodes in a neighborhood and the relay transmission would not significantly impact the transmission of an overloaded candidate relay node. In addition, with extra packets buffered to forward for other nodes, a candidate relay node could have a higher priority of being scheduled for transmission.
- *Receiver-facilitated reduction of redundant relay transmission.* As a node self-determines if it can be a relay in a time slot based on the priority of the cached packet to avoid signaling overhead, there is a likelihood that multiple nodes may attempt to perform relay transmission. Our MAC scheme let the receiver to select the relay as discussed at the end of Section 4.1.2.

From the problem formulation in Section 3, it is clear that the scheduling problem has to determine the values of the four parameter set: $\{t_j\}$, $\{h_j\}$, $\{y_{ij}\}$, and $\{a_{ijk}\}$ to assign a packet to an appropriate transmitter antenna in order to maximize the total weighted rate of the network. In a practical half-duplex network, it is reasonable to divide the problem into two parts: transmitter selection and stream allocation. In the first phase, a set of nodes are selected as transmitter nodes, and for each selected node, it needs to determine the number of packets to transmit in the current transmission duration. Thus the values of $\{t_j\}$, $\{h_j\}$and $\{y_{ij}\}$ are determined. The decision in our scheduling is made based on the transmission priority of the packets in queue, and the antenna constraints of the transmitter nodes and receiver nodes. In the second phase, each selected transmitter node needs to assign its packets to appropriate antennas for transmission based on the number of streams it is allowed to transmit, the priority of the packets, and the channel conditions. Thus, the value of $\{a_{ijk}\}$ is determined. In the next two subsections, we introduce the problem and algorithm for each scheduling phase.

4.1 Determination of Transmitter Nodes and the Number of Transmission Streams

Instead of randomly selecting the transmitter nodes in a TD, in this phase, we propose a *priority-based self-selection* strategy with which an active node self-determines if it can serve as the transmitter and the number of streams to transmit based on the priority of its packets, its transmitter constraint and the decoding constraints of its neighbors. A candidate relay node incorporates the relay packet with its own transmission and participates in the transmitter selection process.

As the selection is performed at the beginning of each TD before any transmissions, the rate information for candidate streams is unavailable. The transmitter node assignment and the number of streams are thus determined with the goal of optimizing the overall priority performance, and the goal of rate optimization is addressed later in the stream allocation phase. The problem in equations (1)-(6) is then reduced to the subproblem formulated as follows:

$$\max \sum_{i\in P_{pkt}} \sum_{j\in R_i\cup\{s_i\}} y_{ij}\mathscr{P}(i); \tag{7}$$

$$\sum_{j\in R_i \bigcup\{s_i\}} y_{ij} \le 1, i \in P_{pkt}; \tag{8}$$

$$\sum_{i\in P_{pkt}} y_{ij} \le N_j^{ant} + (1-t_j)M, j \in N; \tag{9}$$

$$\sum_{m\in \mathscr{V}_j} \sum_{i\in P_{pkt}} y_{im} \le N_j^{ant} + (1-h_j)M, j \in N; \tag{10}$$

$$t_j + h_j \le 1, j \in N; \tag{11}$$

$$\begin{aligned} y_{ij} \le t_j, y_{ij} \le h_{d_i}, t_j, h_j, y_{ij} \in \{0,1\},& \\ i \in P_{pkt}, j \in N;& \end{aligned} \tag{12}$$

where M is a sufficiently large number as defined in section 3. Corresponding to constraints (1)-(3), (8) limits a packet to only one transmitter to avoid simultaneous transmissions of a packet from multiple relay nodes for improved transmission throughput, (9) and (10) represent degree constraints at a transmitter and a receiver respectively. Note that the set P_{pkt} is updated at the beginning of each TD so that the packets that arrive during the previous TD can be included.

4.1.1 Distributed Transmitter Node Selection

A distributed solution for the problem aims at maximizing the objective in (7) while probabilistically satisfying constraints (8)-(12). Let Q_j denote the packet queue at node j, where original packets and relay packets are sorted in a descending order of their priorities. Let N_j^0 be the proposed number of transmission streams, obviously $N_j^0 = \min\{N_j^{ant}, |Q_j|\}$. Denote the l-th packet of node j as $p(j,l)$. Parameter U_j is defined to be the priority of the head-of-the-line packets in node j's queue, i.e., $U_j = \sum_{l=1}^{N_j^0} \mathscr{P}_{p(j,l)}$, which is used as the priority of j for scheduling.

In order to avoid unnecessary channel measurement and message processing at a receiver, our algorithm first selects a candidate set of transmitters. To guide the transmitter selection, we introduce a probability P_j^{TX}, below which an active node j can be selected as a transmitter node. Suppose m, a neighboring node of j, has N_m^{active} neighboring nodes and can decode N_m^{dec} concurrent streams, which can be obtained from periodic Hello messages sent in the two-hop neighborhood of j at the network layer. If the average number of streams from a single transmitter node around a receiver m is known and denoted as $\bar{N}_{\mathscr{V}_m}^{allo}$, in order to not exceed its decoding capacity, m generally only allows $\widetilde{N}_m = N_m^{dec}/\bar{N}_{\mathscr{V}_m}^{allo}$ nodes among its N_m^{active} neighbors to transmit in a TD. That is, each of the nodes around m is allowed to have a probability of $N_m^{dec}/(\bar{N}_{\mathscr{V}_m}^{allo} N_m^{active})$ to serve as the transmitter. As $\bar{N}_{\mathscr{V}_m}^{allo}$ is hard to know before scheduling is performed, a node can at most have a probability of N_m^{dec}/N_m^{active} to serve as the transmitter. The parameter P_j^{TX} of j can then be calculated as follows to consider the decoding capability of all its neighboring receiver nodes:

$$P_j^{TX} = \min_{m\in\mathscr{V}_j} \Big(N_m^{dec}/N_m^{active}\Big). \tag{13}$$

Instead of only considering the decoding capability of the selected receiver nodes which is not available at the selection time, our selection considers the decoding capability of all the neighboring nodes and is more conservative.

With this calculation, when there is only a small number of nodes around each receiver, e.g. P_j^{TX} calculated in equation (13) has a value larger than 1, there is a possibility that all the nodes within a neighborhood are selected as the transmitters. For example, if the network has only two nodes and each node can decode up to four streams, both nodes may be selected as transmitters and it is not possible to complete the transmission. To avoid this problem, when $P_j^{TX} \ge 1$, the value of P_j^{TX} is replaced with $P_j^{TX} = \max_{m\in\mathscr{V}_j}(N_m^{active}/(N_m^{active}+1))$, so that at least one node will be kept as the receiver.

The priority of a node can be attached with periodic Hello messages sent at the network layer, and updated with the data packets sent. The priority of the active nodes not having packets sent in a TD can be predicted as the time moves forward. A node j can then record the maximum priority U_j^{max} and the minimum priority U_j^{min} of all the N_j^{active} active nodes in its neighborhood and itself, and also calculate the average priority $\bar{U}_j$ as $\bar{U}_j = (\sum_{m=1}^{N_j^{active}} U_m + U_j)/(N_j^{active}+1)$.

To avoid extra signaling and control overhead, an active node j *self-decides* if it should be selected as a transmitter node by calculating an index number r_j^{TX} as follows:

$$r_j^{TX} = \begin{cases} (\bar{U}_j - U_j)/(U_j^{max} - U_j^{min}) + \gamma_j & \text{if } U_j^{max} \neq U_j^{min} \\ \gamma_j & \text{if } U_j^{max} = U_j^{min} \end{cases} \tag{14}$$

where the parameter γ_j is uniformly distributed in the range $[0, 1]$ and randomly generated by a node j in each transmission duration (TD) to provide some fairness among nodes. The factor $(\bar{U}_j - U_j)/(U_j^{max} - U_j^{min})$ is used to give the higher priority node a larger probability for transmission. In a TD, if $r_j^{TX} < P_j^{TX}$, node j is selected as a transmitter node; otherwise, it has no right of transmission. Our transmitter selection algorithm gives preference to a node with a higher service priority and/or a larger load and hence longer delay, and thus supports load balancing. Moreover, as the priority parameter dynamically reflects the queuing status of nodes so a node does not always have higher priority than its neighbors, it helps ensure fairness over the network.

Note that in this phase relay packets and original packets are treated equally, and the value of $\{x_j\}$ is determined.

4.1.2 Distributed Determination of the Number of Streams

Through the procedure described next in Section 5, a receiver node estimates the total number of candidate streams it may receive N_j^{rec} and broadcasts it together with the number of streams it is able to decode N_j^{dec}. These two parameters are used at a transmitter node to determine the actual number of transmission streams it is allowed to transmit.

Denote the set of receiver nodes within the transmission range of a transmitter node j as X_j^{rc}. In order to ensure all the receiver nodes in its neighborhood to have high probability of meeting their degree constraints, j constrains its number of sending streams to a number N_j^{allo} as follows:

$$N_j^{allo} = N_j^0 \min_{m \in X_j^{rc}} \left(\frac{N_m^{dec}}{N_m^{rec}} \right). \tag{15}$$

Note that the value N_j^{allo} may be a fractional number. To achieve a higher accuracy in calculating N_j^{allo} than using simple rounding, let $N_{j,0}^{allo} = N_j^{allo} - \lfloor N_j^{allo} \rfloor$. If $N_{j,0}^{allo} > 0$, generate a random variable β_j uniformly distributed in $[0, 1]$. If $\beta_j \leq N_{j,0}^{allo}$, $N_j^{allo} = \lfloor N_j^{allo} \rfloor + 1$; otherwise, $N_j^{allo} = \lfloor N_j^{allo} \rfloor$. So far, the number of streams to be transmitted is determined.

4.2 Allocation to Antennas

In this phase, N_j^{allo} data packets of node j are allocated to N_j^{allo} out of N_j^{ant} antennas for transmission. For a node that does not serve as a relay, it simply considers the first N_j^{allo} data packets in the queue. For a potential relay node, it would waste network resource if it forwards the same packet concurrently with other relay nodes. Our scheduling scheme naturally selects the forwarding nodes based on the relevant priority of the to-be relayed packet and the priorities of the other packets of a relay node. After this self selection process, there are still the possibility that some relay nodes choose the same TD to forward i. To further reduce the chance of unnecessary relay forwarding, when the destination receiver receives multiple relay transmission requests, it selects the relay node with the best channel condition to forward the packet. The rest of the requesting relay nodes can use the slot to send other packets. More details of the relay selection operation are presented in section 5.

The packets may have different destination nodes thus varied link loss, and the spatial channels from different elements of the antenna array undergo different fading. As discussed in [17], the data rate can be improved by opportunistically allocating the packets to transmitted antennas. Moreover, with channel information available at transmitters' side, selection diversity is shown to outperform space-time coding in improving the link reliability [23]. With the goal of maximizing transmission rate, the stream allocation problem is essentially a bipartite maximum matching problem.

Construct a graph $G = (V_1 \cup V_2, E)$ for a transmitter node j. V_1 denotes the set of packets to be allocated to antennas and V_2 denotes the set of transmitting antennas of j. Thus $|V_1| = N_j^{allo}$ and $|V_2| = N_j^{ant}$. Form an edge (v, u) between v and u where $v \in V_1$ and $u \in V_2$, and the weight of the edge is $w_{vu} = \mathscr{R}(v, u)$. Here $\mathscr{R}(v, u)$ is the rate of the stream to transmit a packet represented by node v to its destination node through the antenna represented by node u, which is estimated through signal exchange as discussed in Section 5. If $|V_1| \neq |V_2|$, add dummy nodes to make $|V_1| = |V_2|$ and the edges connected to a dummy node has weight 0.

By solving the maximum weight matching problem formulated above (i.e. using successive shortest path algorithm [25]) and then deleting the dummy nodes and edges connected to them, the optimum solution of the allocation is derived. Let $|V| = |V_1| + |V_2|$, the complexity of the algorithm is bounded by $O(|V| \log |V|)$.

5 PROTOCOL DESIGN

In the previous section, the scheduling is performed in each transmission duration to determine the transmission schedule of the packets, including original packets and relay packets, in the queue of each node. However, the details about cooperative relay transmission, i.e. how to maintain the queue to store relay packets, how to trigger and enable a relay node to transmit relay packets have not been addressed yet. In this section, we propose the protocol to facilitate cooperative relay transmission in a MIMO-based ad hoc network and implement the distributed scheduling algorithm described in Section 4. We first give an overview of the relay operations in Section 5.1, and then describe the details of the protocol in Section 5.2. An example is presented in Section 5.3.

5.1 Relay Operations

There are several challenges arising in integrating the cooperative relay transmission with the cooperative MIMO multiplexing transmission scheme. We propose a few strategies to address the issues, some of which are also mentioned in previous sections, and we summarize them here for the protocol design.

5.1.1 Finding Candidate Relay Nodes

In a conventional relay strategy, a source often broadcasts a relay request explicitly, and waits for replies from the potential relay nodes. This process not only introduces extra signaling overhead, but also adds in delay for relay transmission. Instead, the process of finding candidate relays in our scheme is automatically performed at qualified nodes without involving the source and destination of a packet. Specifically, a node r_i identifies its potential of being a candidate relay node of a packet i which is targeted to d_i when successfully receiving the packet from its sender s_i, either because r_i is idle or because r_i could decode i when receiving its own packet with its multi-packet reception capability. If the destination of the data packet i is also in r_i's neighbor list, r_i temporarily stores i in its buffer with the current priority of i. If i is successfully received by d_i, r_i removes i from its buffer; otherwise, the priority of i is updated as its buffering time in r_i increases. In a dense network where a packet could be overheard and buffered by too many potential relay nodes, to avoid excessive and unnecessary buffering, a node may only buffer a packet with certain probability, or a sender could tag the packets that may need relay.

5.1.2 Triggering of Relay Transmission

Instead of explicitly invoking relay transmission, in our scheme, triggering of relay transmission and selection of relay node is incorporated with normal packet scheduling. If a failed direct transmission is detected, i.e. a candidate relay r_i receives packet i from s_i but does not receive the successful reception acknowledgement for packet i (either through ACK-I or ACK-II as described in section 5.1.4) in the same TD, r_i immediately moves the relay packet i from the buffer to its MAC queue, and treats it as a normal packet waiting for transmission. The node then serves as a relay node in the following TDs. There may be multiple candidate relay nodes for a packet, and the packet to relay is generally placed in different positions of the packet queues in different candidate relay nodes depending on the relative priority of the packets. In a TD, a candidate relay node that has the relay packet scheduled to transmit is implicitly selected as the relay node of the packet. With multiple candidate relay nodes, as long as a subset of the nodes receive a packet from the source, the packet can be relayed to the receiver. Multiple relay nodes and maybe also the source node of i may intend to transmit it in the same TD, if i happens to be a head-of-the-line packet in all of their queues. In order to reduce the chance of unnecessary concurrent transmission, the targeted receiver node counts the number of successful transmission requests for the same packet. The node with the best channel condition is selected to serve as the packet sender and the selection is broadcast by the receiver. In summary, our scheduling strategy triggers relay transmission through the implicit self-selection by candidate relay nodes and explicit selection by the destination receiver to reduce the signaling overhead as well as to avoid redundant transmission.

5.1.3 Constraining the Delay of Relay Transmission

To avoid excessive traffic increase and occupation of network resource, a retransmission threshold F is introduced that a packet is dropped if its reception fails after F TDs has elapsed since its first direct transmission. To ensure that the source node and all candidate relay nodes have a consensus on the packet transmission status, a packet transmitted from its source node is attached with a time-stamp indicating the current elapsed time since its initial transmission, so that candidate relays can record this stamp and update it as the queuing time increases. If the transmission fails continuously over a period of time, e.g. longer than $3F$ TDs since the first direct transmission, a source node may even give up its transmission towards a particular receiver as the continuous failure indicates a long-term brokage of the link, e.g. topology change due to mobility. It may then look for an alternative path to the destination, e.g. through multi-hop relays.

5.1.4 Broadcast of Packet Reception Status

The information about successful or failed reception of a packet is usually broadcast through ACKs. However, as all receivers in a TD send ACK simultaneously as described in Sections 5.2, only nodes that are not receivers in the current TD can receive the ACKs. As a candidate relay node may either serve as a transmitter or a receiver in a TD, it is necessary to inform all of them about the updated reception status, so that successfully received packets can be removed while unsuccessfully received packets can have their priority increased. In addition, a source may not be able to get the ACK if the channel condition from the destination to it is very poor, and a potential relay node also needs the reception status to determine whether the packet should be moved from the buffer to the MAC queue. To address those issues, an extra ACK phase is introduced into the protocol, during which the information included in the first ACK is rebroadcast by nodes that receive it in the current TD. Through the two phases of ACK from multiple nodes, extra diversity is provided to guarantee the correct update of the packet reception status for all the nodes in concern. To differentiate between the two ACK messages, they are named ACK-I and ACK-II respectively. In the proposed MAC scheme, the data transmission can be in burst, so the overhead of ACK signaling is relatively small.

5.1.5 Rate Determination

As described in the protocol, both transmitter nodes and receiver nodes are able to estimate the full channel condition matrix through training sequences. Also, a receiver node can estimate the interference and noise around it, and announce this information to the corresponding senders. With the channel matrix and the interference and noise at the receiver, a transmitter can determine the rate to use for transmission. If a packet is scheduled for its first direct transmission and the link to its destination is estimated to be severe, the source node uses a default moderate transmission rate for its transmission, so as to increase the chance of having some relay node successfully receive the packet as well as avoid wasting the transmission opportunity in the current TD. Note that the transmission of a specific packet is canceled for the current TD if a sender node could not receive response, i.e. CTS, from the corresponding receiver after sending an initial handshaking signal, as it can be expected that the requested receiver is currently a transmitter or the link condition is temporarily poor. However, if the response from a receiver is consecutively missing, e.g. for more than F of transmission requests, it is indicated that the link between the source and destination undergoes relatively long term degradation. In such a case, the source node may still initiate transmission in the following $2F$ TDs and send out the packet using the default moderate transmission rate, in the hope that it can be received and forwarded by some relay nodes in the neighborhood.

5.2 Protocol Details

Based on the above operations, we propose a TDMA-based MAC protocol to support the cooperative relay transmission in a MIMO-based ad hoc network. A time frame is divided into five phases with different transmission duration, namely RTS, CTS, DATA, ACK-I, and ACK-II. Note that slot synchronization is currently achievable in the IEEE 802.11 family of protocols. By taking advantage of various diversity techniques, our scheme effectively increases the SINR of received signals, which helps improve the accuracy of synchronization as well as mitigate the impact of asynchronicity in a distributed scenario. A group of random access codes, called ID code, which are almost orthogonal for different nodes and assigned similarly to that in [26], are used to mask and differentiate simultaneously transmitted control signals from selected nodes, and used for transmission coordination and channel estimation.

RTS In RTS transmission phase, nodes that determine themselves to be transmitter nodes (using algorithm in Section 4.1.1) broadcast RTSs. For a transmitter node j, the RTS message contains the number of streams it plans to transmit N_j^0, its node ID and the IDs of the destination nodes. The preamble of a packet is used as the training sequence (without incurring extra overhead for adding in pilot signal) for channel estimation purpose. The preamble of an RTS message is transmitted rotationally from each antenna so the full channel condition matrix can be estimated at receiver nodes. RTS messages sent from different transmitters are masked by different ID code to allow a receiver to differentiate the messages. As the number of antennas is generally small and only the preamble of the RTS message is transmitted through all antennas, the total transmission delay for channel estimation purpose is small. The full knowledge of the channel as a result of the estimation, however, could enable simultaneous transmission of multiple spatial streams and bring in multi-fold capacity gain [17] and thus delay reduction.

CTS The RTSs are received at receiver nodes, where channel matrices are estimated by extracting the preambles. A receiver node m also estimates the number of streams it may receive $N_m^{rec} = \sum_{j \in \mathscr{V}_m, x_j = 1} N_j^0$. Constrained by its degree of freedom, m can decode at most N_m^{dec} streams simultaneously. If m receives multiple RTSs (from the source and/or candidate relay nodes) on the transmission of i in current TD and is the target receiver of i, it then selects the node r_i which has the best channel condition between r_i and m to forward the packet. Based on the decoding capability and the signal strength received, m estimates the interference plus noise level (SINR) for candidate transmission nodes. In general, SINR can be quantitized into different levels and only the index of level is needed in feedback instead of its absolute value, which can effectively reduce the amount of overhead. Finally, m broadcast a CTS message including SINR, N_m^{rec}, N_m^{dec} and r_i. Note that CTS message is also masked by ID code and the preamble is transmitted rotationally from each antenna of m for transmitter nodes to estimate the full channel condition matrix.

DATA In the DATA phase, a sender first determines the number of streams it is allowed to transmit using the algorithm in Section 4.1.2, based on the information received from CTSs sent by neighboring receivers. It should also select the packets to be transmitted based on the receivers' confirmation for the initial handshaking messages. Specifically, a node should check if it has been selected as the sole forwarder by the receiver if a request for relay transmission is sent earlier. If a node is the source for a packet and the CTS has been missing for more than F times, it would also send out this packet for relay purpose. The transmitter then estimates the transmission rate from each antenna based on the estimated channel condition and interference at a destined receiver, and transmits the packets from the antennas selected using the maximum weight matching algorithm in Section 4.2. A receiver node then differentiates all streams it receives and extracts the data packets targeted for it. Instead of discarding packets transmitted through interference streams, a receiver buffers an overheard packet if it is within the transmission range of the packet destination for potential relay transmission.

ACK-I Receiver nodes broadcast ACKs about those successfully received packets, which include the original sources of the packets. These messages are received by nodes that are not receivers in the current TD.

ACK-II If a relayed packet is received successfully, the source node as well as all the potential relay nodes should remove it from their buffers and queues in order to avoid redundant transmissions. Some of these nodes may not be able to receive the ACKs as they are also in transmitting states during the transmission of ACKs. After the transmission of ACK-I, ACK-II is rebroadcast by non-receiver nodes in the current TD. With the transmission of ACKs in consecutive phases, it not only ensures all candidate relay nodes to learn the packet transmission status, but also guarantees that the original packet sender is informed about the successful transmission of the relay packet. In the case that the channel condition between the source and the destination is poor and ACK-I message from the destination cannot be received by the source node, the rebroadcast of ACK-II messages from intermediate nodes plays an important role to avoid the continuous redundant retransmissions and thus more waste of wireless resources. In this way, a potential relay node that successfully overhears a packet but does not have a functional link towards the destination will also be informed by the sender through ACK-II, so that it will not vainly consider relaying the packet.

5.3 An Example

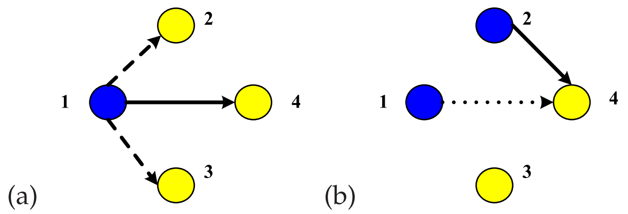

Fig. 3. An example of cooperative relay transmission.

In this section, we give a brief example to explain the process of cooperative relay transmission. In the simple topology shown in Fig. 3, node 1 has a packet to transmit to node 4, node 2 and 3 are in the neighborhood of both node 1 and node 4 but are not in each other's neighborhood. Assume the channels are with good quality between node 1 and node 2/3 and between node 2/3 and node 4, but the channel between nodes 1 and 4 experiences severe fading. In the transmission duration shown in Fig. 3(a), node 1 initiates a direct transmission towards node 4. As node 2 and 3 are both in the receiving mode, they overhear the packet, as indicated by the dashed edges. Perceiving that there is no ACK for the packet from node 4 due to the link failure, node 2 and 3 both store the packet into their own MAC queue and treat it equally with their own direct packet so that they are potential relays for the packet. In a following transmission duration shown in Fig. 3(b), according to the transmitter selection criterion, node 1 and 2 could both be selected as transmitters and node 3 and 4 are still in the receiving mode. Suppose that the priority of the packet from node 1 to node 4 is relatively high, and both node 1 and 2 indicate their preference to send it to node 4 in the RTSs. By receiving the RTSs and completing channel estimation, node 4 selects node 2 as the transmitter for the packet as the channel condition from node 2 to node 4 is better than that from node 1 to node 4, in order to avoid redundant transmission. Therefore, node 1 withholds the transmission, as indicated by the dotted edge, and node 2 successfully relays the packet to node 4. In the ACK-I phase, node 4 feeds back the information about the successful reception. After receiving the ACK, potential nodes (original source or relays) that are currently transmitters, i.e. node 1 and 2, remove the packet from their queues. In order to make sure the packet is also removed from the queues of candidate relay nodes that currently serve as receivers (which are also in the process of sending out ACK to their corresponding transmitters) and are not able to receive ACK-I, e.g. node 3, transmitter nodes that have received the ACK-I, i.e. node 1 and 2, send out ACK-II to further rebroadcast the successful reception information. To this end, the packet is successfully transmitted through the cooperative relay transmission and removed from all queues.

6 PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed algorithms through simulations based on a detailed MATLAB simulator we have built. We consider an ad hoc network with random topology where nodes are distributed uniformly over a $1250m \times 1250m$ area. Each node is equipped with an array of 4 antennas and has a reference transmission range of $250m$ as in a standard IEEE 802.11 wireless network. Both path loss and independent Rayleigh fading are incorporated for each wireless link between an antenna pair. For each node, the number of incoming data packets is Poisson distributed with a given mean value λ and the destination of each packet is chosen at random. The size of a packet is 200 bytes. A simulation result is obtained by averaging over ten runs of simulations with different seeds.

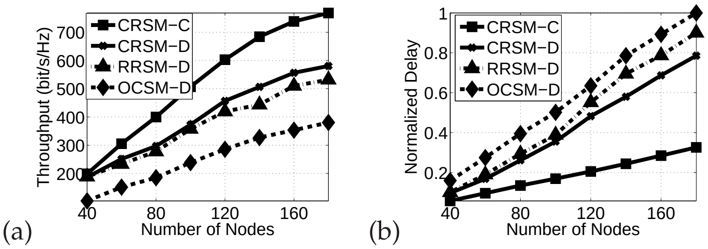

Fig. 4. Impact of node density: (a) Throughput; (b) Normalized delay.

The two-phase scheduling algorithm proposed in Section 4 is implemented based on the MAC protocol described in Section 5. The Cooperative Relayed Spatial Multiplexing schemes proposed in this paper are named as CRSM-C or CRSM-D respectively, depending on whether a centralized scheme or a distributed scheme is used for the determination of transmitter nodes and the number of transmission streams. Correspondingly, we implemented two reference TDMA-based schemes in the distributed manner for performance comparison. One scheme is the Distributed Opportunistic and Cooperative Spatial Multiplexing (OCSM-D) scheme proposed in [17] which does not involve a relay transmission, the other scheme is also based on OCSM-D but have random relay selection enabled for performance enhancement, which is denoted as Distributed Random Relayed Spatial Multiplexing (RRSM-D). The metrics we use are throughput and normalized delay. Throughput is the total effective data rate of the network averaged over the number of transmission durations. Delay time is defined as the number of transmission durations a packet waits in the queue before it is removed from the MAC queue. The transmission delay includes the time for transmission of control packets. For the convenience of comparison, the results of delay are normalized to the maximum value in each figure. We investigate the impact on network performance due to four factors, namely node density, link failure ratio, packet arrival rate and retransmission threshold. The retransmission threshold defined in Section 5.1 is in the unit of TD, and a packet is dropped from both the source queue and queues of candidate relay nodes when the time lasted from the initial packet transmission exceeds the threshold. If not otherwise specified, the number of nodes in the network is 100, the link failure ratio is 0.3, the average packet arrival rate λ is 0.5 and the retransmission threshold is 8.

6.1 Impact of Node Density

The impact of node density is shown in Fig. 4. Increased node density leads to heavier traffic and also provides

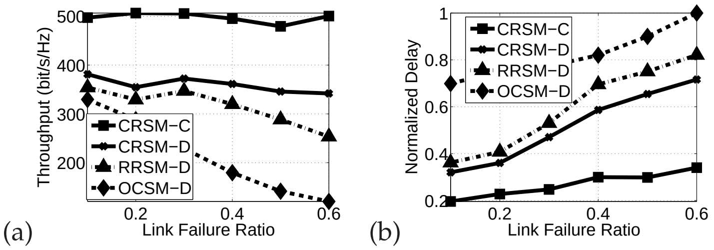

Fig. 5. Impact of link failure ratio: (a) Throughput; (b) Normalized delay.

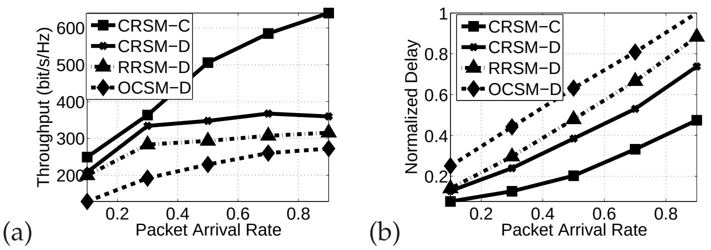

Fig. 6. Impact of packet arrival rate: (a) Throughput; (b) Normalized delay.

more links among nodes in a network. In case of severe links, the two CRSM schemes have a higher possibility of finding candidate relay nodes to assist in transmission by taking advantage of the improved connectivity. In Fig. 4 (a), CRSM-D is observed to improve the throughput up to 53% compared to OCSM-D. Effective scheduling of packets with relay also reduces the queuing delay as seen in Fig. 4 (b). Compared with RRSM-D which uses a preselected relay, CRSM-D implicitly and adaptively selects the node scheduled to transmit the first as the relay, which not only helps to speed up relay forwarding but also helps to balance load among nodes. These benefits are reflected in the up to 14% improvement in throughput and 13% reduction in delay.

6.2 Impact of Link Failure Ratio

A link is considered to be failed if a packet transmitted through it can not be received successfully by its receiver. Link failure can be a result of path loss, deep fading of channels, mobility of nodes, etc. We use link failure ratio (LFR) to model the percentage of failed links over all direct data transmission links between each pair of source and destination in the network. The failed links are randomly selected based on the link failure ratio and they are disconnected throughout the current run of simulation. The two CRSM schemes are shown to have a robust performance under different link failure ratios, as in Fig. 5. In Fig. 5 (a), while the throughput of OCSM-D degrades tremendously with increasing LFR, only a slight throughput degradation is observed with both CRSM schemes. As the CRSM schemes can smartly leverage the functional relay links to send packets out, it helps maintain the throughput performance. The throughput of CRSM-D is three times that of OCSM-D when a frequent link breakage occurs at $LPF = 0.6$, and the delay reduction is up to 50%. A higher link breakage ratio would lead to increased delay. The significant performance improvement demonstrates the effectiveness of adaptively using relay in MIMO transmissions to improve reliability in a harsh transmission environment. Although RRSM-D also supports the use of relay, the random relay selection which does not take advantage of the channel conditions to select node for more reliable relay transmission is observed to be less effective than the adaptive scheme of cooperative relay proposed in this paper, as the throughput drops faster with increasing LFR compared with CRSM-D. RRSM-D has up to 26% lower throughput and 25% higher delay compared with CRSM-D.

6.3 Impact of Packet Arrival Rate

The mean packet arrival rate λ captures the traffic load in a network. By adaptively using cooperative relay transmissions, high rate links are more efficiently utilized to schedule heavier traffic load. In Fig. 6 (a), even with the heaviest traffic load, CRSM-D still achieves 35.7% higher throughput than OCSM-D. Although higher traffic increases queuing delay of packets due to limited network capacity, the delay of CRSM-D scheme is about 30% lower than that of OCSM-D. This demonstrates that even in the heavy traffic load condition, the relay can effectively improve performance. The node with the lowest load will be naturally selected as the relay. Meanwhile, CRSM-D consistently outperforms RRSM-D by up to 20% higher throughput and 19% lower delay, which further demonstrates the advantages of using adaptive cooperative relay instead of conventional relay schemes. In the case of heavy load, the packets are backlogged in the queue of nodes, and the delay increases significantly.

6.4 Impact of Retransmission Threshold

Retransmission is a common strategy used to deal with temporary transmission failure. The performances of CRSM and OCSM are compared in Fig. 7 under different values of the retransmission threshold F, as introduced in Section 5. In CRSM schemes, packets experienced direct transmission failure can be forwarded through relay links which may have better link conditions than the direct link. With increased value of F, both CRSM schemes keep a nearly constant throughput values, while OCSM-D undergoes 33.5% throughput reduction from $F = 2$ to $F = 14$. Even though more retransmissions help to increase the probability of successful packet reception, transmissions over poor links for a longer period of time would consume more network resources. On the contrary, both CRSM schemes actually take advantage of a larger F to conduct relay transmissions through adaptive scheduling. The delays of two OCSM schemes and CRSM-D scheme all increase with F with the increase of time to keep the packets in buffers, while CRSM-D remains to have much lower delay (up to 40%) than OCSM-D under all values of F. With varied valued of F, CRSM-D still takes advantage of the adaptive relay selection to achieve both higher throughput and lower delay than RRSM-D.

7 RELATED WORK

In recent years, many efforts have been made in developing MAC schemes to support MIMO transmission and cooperative diversity in ad hoc networks.

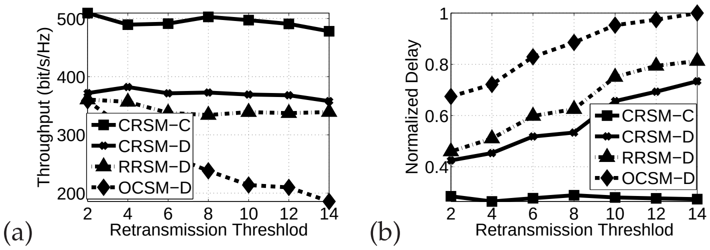

Fig. 7. Impact of retransmission threshold: (a) Throughput; (b) Normalized delay.

In [9], spatial diversity is explored to combat fading and achieve robustness. Layered space-time multiuser detection and its role in PHY-MAC cross-layer design are analyzed in [11]. In [12], spatial multiplexing with antenna subset selection for data packet transmission is proposed. The optimization considerations for MAC layer design in ad hoc networks with MIMO links is discussed in [13], and unified representation of the physical layer capabilities of different types of smart antennas, and unified medium access algorithms are presented in [27]. The authors of [15] exploits the benefits of using multiple antennas to achieve flow-level QoS in multi-hop wireless networks. In [17], an opportunistic and cooperative multiplexing scheme is proposed to better exploit spatial/multiuser diversity to improve transmission capacity and support different traffic demands in the network. An adaptive and distributed solution considering the heterogeneity of antenna array sizes of network nodes is presented in [28]. However, none of these solutions considers the potential benefits of using cooperative relay in MIMO-based ad hoc networks.

Though cooperative diversity has been extensively studied theoretically [19], there are limited work that investigate the solution of scheduling in practical network implementations. In [20], the authors proposed relaying strategies to increase the system reliability and the work in [29] tries to emulate the function and achieve the transmit diversity gain of using space-time codes in a distributed manner through node cooperation without the use of multi-antenna arrays. A multi-layer approach for exploiting virtual MISO links in ad hoc networks is presented in [14] and an optimal relay assignment is discussed in [30]. A relay selection scheme is proposed in [31] for multi-node decode-and-forward cooperative scenarios via the available partial channel state information (CSI) at the source and the relays, and a distributed relay selection scheme is proposed in [32] using finite-state Markov channels. However, the scale of network considered in these studies is relatively small, and they do not provide MAC protocols to implement in a wireless multi hop wireless mesh network. The utilization of cooperative relay in wireless cognitive radio networks is investigated in [21] and a new MAC protocol is proposed. In this work, cooperative relay is only considered for networks with single antenna nodes, while it requires specific strategies to leverage the benefits of cooperative relay in a MIMO-based network. In [33], the authors analytically considers a general multiple-antenna network with multiple relays in terms of the diversity-multiplexing tradeoff. In [16], retransmission diversity through node cooperation is investigated in specific homogeneous omni-directional and smart antenna networks. Cooperative spatial multiplexing is systematically implemented with hybrid ARQ in [34], however, it lacks a detailed algorithm and protocol to specifically enable cooperative transmission which is generally very challenging to achieve in a dynamic network.

Our work distinguishes itself from the aforementioned work in that it adaptively adopts relay forwarding with cooperative MIMO multiplexing to significantly improve the throughput while supporting transmission reliability. The initial results have been presented in [35]. In this paper, we present more details of our design and perform more extensive simulations to demonstrate the functionality of the proposed algorithms.

8 CONCLUSIONS

Ad hoc networks are popularly used in military and emergency rescue environments. In addition, there are increasing interests in applying ad hoc networks to connect various wireless devices to enable more powerful wireless applications and mobile computing capabilities. All these applications require higher network throughput and reliability. In this work, we design scheduling algorithms and MAC protocol to enable cooperative relay transmission in MIMO-based ad hoc networks, in order to jointly exploit the cooperative multiplexing gain and cooperative diversity gain to achieve overall higher data rate and lower delay under harsh channel conditions. We formulate the problem of packet scheduling with cooperative relay in MIMO ad hoc networks as an integer programming problem, and propose both centralized and distributed solutions to support relay transmissions. We also design an effective MAC protocol to facilitate the implementation of the distributed scheduling algorithm. Through extensive simulations, our scheme is shown to outperform the reference MIMO scheme which does not use relay or employs random relay selection, with significantly higher throughput and reduced average delay. This demonstrates the importance of incorporating relay transmissions in MIMO-based ad hoc networks and the effectiveness of the proposed algorithm in enabling concurrent MIMO and relay transmissions.

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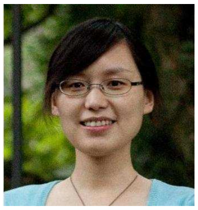

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