A MAC Protocol for Maximum Stream Allocation Depending on the Number of Antennas and Received RTS Packets in MIMO Ad Hoc Networks

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Abstract—MIMA-MAC is the most attractive MAC protocol for MIMO ad hoc networks, which consist of nodes with multiple antennas. MIMA-MAC, however, uses only a half of antennas for data transmission regardless of the number of antennas or transmission demands of neighboring nodes. In this paper, we propose a MAC protocol for MIMO ad hoc networks with Parallel RTS Processing (PRP-MAC) which determines the maximum allowable number of data streams after receiving up to 2 RTS packets at a receiver. PRP-MAC can maximize the number of transmitted data streams regardless of collision of RTS packets, the number of transmission demands from neighboring nodes and the number of antennas at each node. Our simulation results show that PRP-MAC can enhance the network throughput, and decrease the amount of control bytes per data packet compared with MIMA-MAC. In addition, we also show the availability of PRP-MAC in antenna-heterogeneous environments.

I. INTRODUCTION

In recent years, the rapid growth of wireless communication technologies has been leading us to the future ubiquitous society. Wireless devices are expected to be attached on various tools and appliances in order to exchange miscellaneous information, and therefore, various types of networks are thought to exist and collaborate with each other. In such environments, communication should be successfully performed even if infrastructures are unavailable. The Mobile Ad hoc NETwork (MANET) [1] is expected to be one of the most essential techniques in the ubiquitous society because it is distributedly controlled by nodes and does not require any infrastructures. Due to the characteristic of MANET as a distributedly controlled network, techniques and protocols for conventional central control networks cannot be adapted to MANET, and thus, a lot of techniques for MANET have been proposed.

On the other hand, Multiple Input Multiple Output (MIMO) is considered as a key technique for future high-speed communication [2]. In MIMO, multiple data streams are transmitted from multiple antennas on the same channel at the same time, and received by multiple antennas. At the receiver, signals are separated into each transmitted stream by Spatial Multiplexing (SM) techniques [3]. Hence, data streams equivalent to the number of antennas can be transmitted at the same time by using MIMO. In order to achieve high-speed communication in MANET, MIMO ad hoc networks have recently attracted much attention, and a lot of Medium Access Control (MAC) protocols to exploit the potential of MIMO have been proposed [4]-[9].

Among the MAC protocols for MIMO ad hoc networks, MAC protocol Mitigating Interference using Multiple Antennas (MIMA-MAC) [9] is the protocol based on only the exchange of Request to Send (RTS) packets and Clear to Send (CTS) packets like IEEE802.11 MAC protocol [10]. MIMA-MAC has 2 contention slots constituted by an RTS slot and a CTS slot in a fixed-size frame, and is capable of simultaneous data reception from 2 transmitters. In MIMA-MAC, however, stream allocation is not based on transmission demands of neighboring nodes, and the number of transmitted streams must be a half of the number of antennas. Then, the number of transmitted or received streams is not always maximized.

In this paper, we propose a MAC protocol for MIMO ad hoc networks with Parallel RTS Processing (PRP-MAC) which can maximize the number of transmitted data streams regardless of collision of RTS packets, the number of transmission demands from neighboring nodes and the number of antennas at each node. In PRP-MAC, a node which receives an RTS packet waits for another RTS packet. Therefore, it can determine the maximum allowable number of data streams after receiving up to 2 RTS packets, and communication can be performed at the maximum receivable number of data streams. Our simulation results show that PRP-MAC can enhance the network throughput, and decrease the amount of control bytes per data packet compared with MIMA-MAC. In addition, we also show the availability of PRP-MAC in antenna-heterogeneous environments.

II. RELATED WORK

A. MAC protocols for MIMO ad hoc networks

If nodes with multiple antennas perform ad hoc communication, they construct a MIMO ad hoc network and communicate by using multiple antennas. A lot of MAC protocols
exploiting the potential of MIMO have been proposed [4]-[9]. Among them, MIMO MAC protocol for Ad hoc Networks (MIMOMAN) [8] is the only protocol that considers multi-stream transmission in heterogeneous environments. However, it needs a control channel separated from a data channel. Stream Controlled Multiple Access (SCMA) [4] is capable of distributed scheduling and antenna allocation by collecting transmission demands from nodes within 2 hops, and is expected to improve the throughput by simultaneous communication among multiple nodes. However, it needs a large number of control packets, and the throughput is not always improved because its scheduling is performed distributedly and stochastically. On the other hand, MIMA-MAC [9] needs only RTS and CTS packets, and can have 2 pairs of transmitters and receivers communicate simultaneously by simple RTS-CTS exchanges.

B. MAC protocol Mitigating Interference using Multiple Antennas (MIMA-MAC)

MIMA-MAC is a MAC protocol which enables simultaneous communication of 2 pairs of transmitters and receivers in MIMO ad hoc networks. MIMA-MAC uses RTS and CTS packets of IEEE802.11 MAC, and has 2 pairs of transmitters and receivers communicate simultaneously in a fixed frame.

Fig. 1 shows the operation example of MIMA-MAC. We assume that each node has 4 antennas. In addition, we also assume that communication from node A to node B and from node C to node D is performed in Fig. 1(a), as a case of multiple transmitters, and communication only from node A to node B is performed in Fig. 1(b), as a case of single transmitter, respectively. Here, neighboring nodes are within communication range and 2-hop neighboring nodes are within carrier sense range. As shown in Fig. 1, MIMA-MAC uses fixed-size frames which consist of 2 contention slots, a training slot, a data slot and ACKnowledgement (ACK) slot, and each contention slot has backoff minislots in order to decrease the probability of collision.

First, we explain the operation when there are multiple data transmitters among neighboring nodes shown in Fig. 1(a). In the contention slot 1, node A transmits RTS packet. Here, Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is used for contention, and each data transmitter starts transmission from the backoff mini slot chosen in advance. In this case, node C can listen to a signal from node A, and then node C cannot start transmitting an RTS packet in the contention slot 1. Node B can receive RTS packet from node A, and transmit CTS packet back to node A. Next, node C transmits an RTS packet to node D and node D transmits a CTS packet back to node C in the contention slot 2. In this frame, node A and node B, which exchanged RTS packets and CTS packet in the contention slot 1, use training slot 1 and ACK slot 1, respectively, and node C and node D use training slot 2 and ACK slot 2, respectively. In the data slot, each data transmitter transmits data packets with a half of their antennas (2 antennas in this example). Therefore, MIMA-MAC can have 2 pairs of transmitters and receivers communicate simultaneously within a frame.

However, MIMA-MAC does not allocate transmission antennas based on transmission demands of neighboring nodes, and data transmitters always use only a half of their antennas for data transmission. Even if there is only a data transmitter around a data receiver, like data transmitter A and data receiver B in Fig. 1(b), the data transmitter transmits 2 data streams with 2 antennas. However, this data transmitter can transmit 4 data streams with 4 antennas at most because there is no other data stream from any neighboring nodes. Moreover, if RTS packets for the same node collide in either of contention slots, the number of data streams cannot be maximized in that frame because no pair of transmitter and receiver is formed in the contention slot where collision of RTS packets occurred. In addition, MIMA-MAC has another problem that it is not adapted in antenna-heterogeneous environments, because the number of antennas on data transmitters must be less than that on data receivers in order to successfully separate all the data streams at data receivers.

III. PROPOSED PROTOCOL

Here, we propose a new MAC protocol for MIMO ad hoc networks called PRP-MAC, which determines the maximum allowable number of data streams after receiving up to 2 RTS packets at a receiver. PRP-MAC can maximize the number of transmitted data streams regardless of collision of RTS packets, the number of transmission demands from neighboring nodes and even the number of antennas at each node.

A. Control packets in PRP-MAC

PRP-MAC uses RTS packets and 2 types of CTS packets. Fig. 2 shows the contents of each control packet in PRP-MAC.
In PRP-MAC, RTS packets and CTS packets have the number of the maximum transmitted data streams and the maximum allowable data streams, respectively, in order to enable communication in antenna-heterogeneous environments.

RTS packets notify the transmission demand and the number of maximum transmitted data streams \( N_{\text{max}} \). The training symbols are carried in RTS packets in PRP-MAC. On the other hand, CTS packets in PRP-MAC are used to notify the number of maximum allowable data streams to each RTS packet transmitter. In addition, the nodes receiving a CTS packet start Network Allocation Vector (NAV) period and stop generating RTS packets. CTS packets are transmitted at the maximum transmission power in order to avoid interference from all the nodes that possibly interfere data reception. In PRP-MAC, CTS packets can store up to 2 RTS packet transmitters’ ID. We introduce 2 types of CTS packets for different aims.

- CTS packet for the Same receiver (CTS-S) : used if a node receives 2 RTS packets for it, or if a node receives only an RTS packet for it. In the latter case, CTS-S packet has only 16 Bytes excluding the transmitter ID 2 and the number of data streams from it.
- CTS packet for Different receivers (CTS-D) : used if a node receives an RTS packet for it and an RTS packet for another node. In this case, IDs of both RTS packet transmitters are stored in the CTS-D packet.

A node receiving an RTS packet for itself waits for another RTS packet and determines the number of maximum allowable data streams for each RTS packet transmitter. Fig. 3 shows the algorithm for the determination of the number of maximum allowable data streams. As shown in Fig. 3, the number of maximum allowable data streams is determined by \( N_{\text{max}} \) stored in RTS packets and the number of antennas of the receiver. This algorithm calculates \( \text{cts\_num\_stream\_a} \) and \( \text{cts\_num\_stream\_b} \) and they are stored in a new CTS packet.

Other than these control packets, PRP-MAC needs ACK packets. The ACK packet used in PRP-MAC is almost the same as that of IEEE802.11 MAC. However, if a node successfully receives data packets from 2 data transmitters, it stores both data transmitters’ ID in an ACK packet. Therefore, the size of an ACK packet may be 20 Bytes including 2 IDs, while it is basically 14 Bytes for an ID.

These control packets are transmitted on single stream. Only data packets are transmitted on multiple streams using multiple antennas. Since the transmission power is divided evenly for each stream in multi-stream transmission, the transmission power of RTS packets must be adapted considering the transmission range of data packets. Assuming a node has \( N \) antennas, the transmission power of RTS packets should be less than \( 1/N \) of its maximum transmission power.

### B. Time structure of PRP-MAC

Fig. 4 shows the time structure of PRP-MAC. In PRP-MAC, we define a control packet slot as a basic time unit. A control packet slot is longer than transmission duration of any control packets. Since transmission duration of data packets is much longer than a control packet slot, data packets are transmitted over multiple control packet slots. Each control packet slot has backoff mini slots for the random access based on CSMA/CA. In order to avoid collision of RTS and the other packets, the first mini slot in a control packet slot is used for the start of CTS, data and ACK packets, and the other mini slots are used for the random access of RTS packets.

#### C. Operation example in PRP-MAC

Fig. 5 shows the operation example in PRP-MAC where each node has 4 antennas. In Fig. 5, arrows in the left of each figure show the flow of data packets. Now, we define 2 control packet slots just after transmitting an RTS packet as the first CTS slot and the second CTS slot, respectively.

1) **Operation of data transmitters**: First, a data transmitter starts transmission of an RTS packet from a backoff mini slot chosen in advance based on CSMA/CA. In PRP-MAC, since a node which has transmitted an RTS packet may receive a CTS packet in the first CTS slot or in the second CTS slot, it waits for a CTS packet until the second CTS slot. If it receives a CTS-S packet including its ID, it starts data transmission from the next control packet slot (node A and C...
in Fig. 5(a), node A in Fig. 5(b) and node C in Fig. 5(c). On the other hand, if it receives a CTS-D packet including its ID, it starts data transmission from the control packet slot after next (node A in Fig. 5(c)). These procedures help PRP-MAC avoid collision of CTS packets. If the data transmitter receives a CTS-D packet including its ID in the first CTS slot and another CTS packet including its ID in the second CTS slot, it transmits data streams with the number of antennas determined by the CTS-D packet received in the first CTS slot. Then, PRP-MAC can avoid collision of data packets at the receiver which has transmitted a CTS-D packet in the first CTS slot.

2) Operation of RTS packet receivers: In PRP-MAC, after receiving an RTS packet, the node waits for another RTS packet in the next control packet slot. If it receives another RTS packet for itself or does not receive any more RTS packets while waiting, it generates a CTS-S packet (node B in Fig. 5(a), node B in Fig. 5(b) and node D in Fig. 5(c)). This case includes also the case where collision of RTS packets occurs and the receiver cannot receive an RTS packet correctly. On the other hand, if it receives an RTS packet for the other node while waiting, it generates a CTS-D packet (node B in Fig. 5(c)). A node which generates a CTS packet determines the number of maximum allowable data streams for each data transmitter by means of the algorithm shown in Fig. 3, and stores it in the CTS packet. In PRP-MAC, the number of maximum allowable streams is determined after receiving up to 2 RTS packets. Therefore, if there is only an RTS packet transmitter among neighboring nodes like Fig. 5(b), this node is allowed to use all the antennas (4 antennas in this example) for data transmission. Moreover, if only an RTS packet is correctly received due to collision of RTS packets, the RTS packet receiver can allocate all the antennas for data transmission to the node which has transmitted the correctly received RTS packet. Hence, PRP-MAC can maximize the number of data streams regardless of the number of transmission demands or collision of RTS packets.

After receiving data packets, the node which has transmitted a CTS-S packet starts transmitting an ACK packet in the next control packet slot. On the other hand, the node which has transmitted a CTS-D packet starts transmitting an ACK packet in the control packet slot after next. This procedure helps PRP-MAC avoid collision of ACK packets.

D. Discussion on the number of simultaneous reception

PRP-MAC can be extended so that the number of simultaneous transmitters is increased to more than 2. However, the more simultaneous transmitters are, the fewer data streams a node can transmit. Therefore, this extension is not beneficial for data transmitters. Moreover, this extension rule does not yield any advantage for data receivers which have only 2 antennas because such nodes cannot receive more than 2 data streams. Considering the recent trend of downsizing of nodes, the spread of nodes with a lot of antennas is not expected. Therefore, we conclude that this extension is ineffective, and consider only the original version of PRP-MAC.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of MIMA-MAC and PRP-MAC through computer simulations. First, since MIMA-MAC is not adapted to antenna-heterogeneous environments, we set that all the nodes have the same number of antennas. Here, we evaluate the network throughput and the amount of control bytes per data packet.

Table I shows the simulation parameters. In order to evaluate the performance on MAC layer, signal reception of RTS, CTS and ACK packets is based on Signal to Interference and Noise Ratio (SINR) threshold in these simulations, and it is assumed that data communication using MIMO is performed successfully.

The simulation scenario is as follows. First, a fixed number of
TABLE I
SIMULATION PARAMETERS.

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<tr>
<td>Simulation time</td>
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<tr>
<td>Number of nodes</td>
<td>40</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>4</td>
</tr>
<tr>
<td>Transmission power (RTS, ACK)</td>
<td>24.5dBm</td>
</tr>
<tr>
<td>Transmission power (data)</td>
<td>24.5dBm/stream</td>
</tr>
<tr>
<td>Transmission power (CTS)</td>
<td>30.0dBm</td>
</tr>
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<td>Threshold of signal reception</td>
<td>−63.5dBm</td>
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<tr>
<td>Threshold of carrier sense</td>
<td>−70.4dBm</td>
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<tr>
<td>SINR Threshold</td>
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<td>Maximum communication range</td>
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<td>Carrier sense range</td>
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<td>Destination range</td>
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<td>Backoff mini slot size</td>
<td>2 symbol durations</td>
</tr>
<tr>
<td>Number of backoff mini slots</td>
<td>15</td>
</tr>
<tr>
<td>Control packet slot size</td>
<td>128 symbol durations</td>
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TABLE II
SIZE OF EACH CONTROL PACKET.

<table>
<thead>
<tr>
<th></th>
<th>MIMA-MAC</th>
<th>PRP-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTS</td>
<td>20 Bytes</td>
<td>21 Bytes</td>
</tr>
<tr>
<td>CTS</td>
<td>14 Bytes</td>
<td>16 or 24 Bytes</td>
</tr>
<tr>
<td>ACK</td>
<td>14 Bytes</td>
<td>14 or 20 Bytes</td>
</tr>
</tbody>
</table>

Fig. 6. Number of transmitted packets versus number of data transmitters. Data transmitters are selected randomly, and data receivers are selected within the destination range of each data transmitter. After each data transmitter generates 20 data packets, it quits transmitting and a new data transmitter and a new data receiver are selected. Here, we assume that the number of transmitted data packets is the same as the number of transmitted data streams because the number of data streams is not determined when a transmitter sends an RTS packet in PRP-MAC.

A. Network throughput

First, we evaluate the performance of the network throughput. Fig. 6 shows the number of transmitted data packets versus the number of data transmitters. Here, the number of transmitted data packets denotes the total number of data packets transmitted in the whole network during the simulation time. In Fig. 6, it is found that PRP-MAC can transmit more data packets than MIMA-MAC regardless of the number of data transmitters. The reason is that in PRP-MAC a node can receive the same number of data streams as antennas simultaneously, while in MIMA-MAC the number of received data streams may be a half of antennas if a node receives only an RTS packet in a frame. Therefore, it is shown that PRP-MAC can enhance the network throughput compared with MIMA-MAC.

B. Amount of control bytes per data packet

Next, we evaluate the amount of control bytes per data packet. Table II shows the sizes of each control packet. As shown in Table II, each control packet size of PRP-MAC is greater than that of MIMA-MAC because the number of maximum transmitted data streams and maximum allowable data streams are stored in RTS and CTS packets, respectively, and IDs of 2 data transmitters may be stored in CTS and ACK packets.

Fig. 7 shows the amount of control bytes per data packet versus the number of data transmitters. In Fig. 7, it is found that PRP-MAC can decrease the amount of control bytes per data packet compared with MIMA-MAC. The reason is that PRP-MAC can transmit more data streams within a 4-way handshake (RTS, CTS, data and ACK) than MIMA-MAC.

C. Percentage of antenna utilization

Finally, we simulate PRP-MAC in antenna-heterogeneous environments and investigate the percentage of antenna utilization. Fig. 8 shows the simulation scenarios for the percentage of antenna utilization. We use these 2 scenarios in order to create the cases shown in Fig. 5(a) and 5(c). In these simulations, the number of antennas on each node is selected randomly between 2 and 6. Here, the number of received streams must be equal to or less than the number of antennas on data receivers in order to correctly separate each data stream. That is, we must show that there is no case where the percentage of antenna utilization is more than 100% in order to prove the availability of PRP-MAC in antenna-heterogeneous
environments. In addition, since the goal of PRP-MAC is to maximize the number of received data streams anytime, we investigate the ratio of the case where the percentage of antenna utilization is 100%.

Table III shows the ratio of each category by the percentage of antenna utilization at data receivers. No case of more than 100% happens at any receiver in both scenarios. The reason is that PRP-MAC can limit the number of data streams by the algorithm shown in Fig. 3 and the specification of the number of allowable streams in CTS-D packets. This result proves that PRP-MAC is available in antenna-heterogeneous environments. However, the percentage of antenna utilization at data receivers is not always 100%. We discuss the reasons below.

First, when the number of antennas on a data receiver is more than the total number of antennas on data transmitters, the percentage of antenna utilization at the data receiver cannot be 100%. Second, in scenario 2, the number of streams transmitted from node C to node D is limited by the CTS-D packet from node B in order to successfully receive all the data streams at node B. In these 2 cases, there is no way to receive more data streams in the given scenarios. However, there is the only case where PRP-MAC cannot maximize the number of data streams in scenario 2. Assuming each node has 4, 6, 3 and 2 antennas, respectively, node B allocates 3 and 3 streams to node A and C, respectively, by the CTS-D packet. However, node D can receive only 2 streams. Therefore, node C can transmit only 2 streams, and node B receives 5 streams in total although it has 6 antennas. This is the reason why the case of less than 100% at node B in scenario 2 is more than that in scenario 1.

Here, we show a solution of this problem. In the above example, since node C can learn from the CTS packets transmitted by node D that node D has only 2 antennas, node C can write the number of maximum transmitted streams as 2 in its RTS packet when it transmits new data packets to node D. Then, if the same scenario happens, node B can allocate 4 and 2 streams to node A and C, respectively. Therefore, by learning the number of antennas on neighboring nodes from the previous CTS packet, PRP-MAC can realize maximum stream allocation in the next communication.

V. CONCLUSION

In this paper, we have proposed a new MAC protocol for MIMO ad hoc networks called PRP-MAC, which can maximize the number of transmitted data streams by determining the maximum allowable number of data streams after receiving up to 2 RTS packets at a receiver. Our simulation results show that PRP-MAC can enhance the network throughput and decrease the amount of control bytes per data packet regardless of the number of transmitters in the network. In addition, we also show that PRP-MAC is available even in antenna-heterogeneous environments.

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REFERENCES