Abstract
IEEE 802.11 MAC does not use RTS/CTS exchange in multicast/broadcast mode. This may cause throughput loss and packet collision by hidden terminals. We propose a new cross-layer ad hoc multicast protocol, named MIMO-CAST, to improve efficiency of IEEE 802.11 MAC. MIMO-CAST builds a multicast tree on-demand by using control packets exchange. To reduce duplicated transmissions, MIMO-CAST employs Multi Point Relay with which only designated nodes forward packets and all nodes in the network hear those packets. It also exploits Multiple-Input Multiple-Output (MIMO) by giving different weights to its multiple antennas so that a node can receive from one neighbor while blocking the interference from other nodes. We investigate the performance improvement of MIMO-CAST through a simulation study.

I. INTRODUCTION
In modern wireless communications, multiple-input multiple-output (MIMO) systems [1] have lately attracted considerable attention from researchers since the multiple antenna arrays at both ends can provide significant performance improvement over Single-Input Single-Output (SISO) systems. MIMO can increase throughput and data rate without amplifying transmission power or broadening bandwidth. Several MAC protocols [2-4] have been proposed recently to leverage MIMO advantages. They, however, focus on unicast. Little work has been dedicated so far to multicast/broadcast protocols explicitly for MIMO radios.

The IEEE 802.11 MAC protocol does not use RTS/CTS exchange in multicast/broadcast transmission mode to prevent CTS explosion. If multiple nodes returned CTS, they would cause congestion defeating the very purpose of CTS. ACK is also removed for the same reason. Random delay before sending out packets while sensing for other transmissions is applied to avoid collisions. However, the extra delay cannot prevent collision from hidden terminals since the latter cannot be detected. To alleviate the hidden terminal problem, very large random delays must be used, in the order of multiples of packet transmission times.

In this study, we propose a new multicast protocol, named MIMO-CAST, which alleviates the hidden terminal problem of IEEE 802.11 MAC. MIMO-CAST builds a multicast tree by exchanging control packets like on-demand multicast protocols do. To eliminate superfluous forwarding, MIMO-CAST employs a Multi Point Relay (MPR) [12] scheme with which only designated nodes, called MPR nodes, retransmit the message. Different from other ad hoc multicast protocols, the multicast tree consists of only selected MPR nodes so that the minimum number of retransmissions and energy is applied to packet delivery. To suppress remaining possibility of hidden terminal collision, MIMO-CAST exploits the selective reception ability of the MIMO systems. Each node picks different weights for its multiple antennas so that a node can receive a signal from one neighbor while instantly blocking the interference signals from other nodes.

The main contribution of this study is the first cross-layer multicast protocol design that exploits benefits of multiple antennas. The MPR scheme used in this study was first introduced in [12] and the multicast tree creation and maintenance follows common on-demand multicast protocol’s mechanisms, in particular ODMRP [7].

The rest of the paper is organized as followed: Section II illustrates the related works; Section III describes the details of the proposed protocol. In Section IV, simulation results are presented and conclusion will be on Section V.
II. RELATED WORKS

A. Ad Hoc Multicast Protocols

Several ad hoc multicast routing protocols have been proposed in the literature [5-10]. Some protocols rely on proactive mechanisms that periodically exchanges or floods route information to maintain and discover the route, whereas on-demand multicast protocols exchange routing information only when it is necessary. Thus, on-demand routing achieves significant advantages by reducing control packet overhead and saving limited resources.

In general, on demand routing protocols employ two-way handshaking to find a route between a sender/receiver pair. The sender floods a request packet into the network and the receivers respond with reply packets. To reduce overhead of packet flooding, the local recovery approach is introduced. Namely, an alternative route to the destination is searched locally upon detecting route disconnection. Adaptive Demand-Driven Multicast Routing (ADMR) [5] and Multicast Ad hoc On-demand Distance Vector protocol (MAODV) [6] are two examples of an on demand multicast protocol following this approach. They first build a multicast tree between a source and receivers and on detection of a broken link try to repair the route locally.

Another popular on demand multicast routing protocol, On Demand Multicast Routing Protocol (ODMRP) [7], relies instead on periodic network-wide flooding for route discovery and maintenance. ODMRP periodically updates a forwarding mesh instead of a multicast tree and data is delivered via the mesh. Periodic mesh refresh and redundant data forwarding ensure higher packet delivery ratio and robustness against mobility and unreliable wireless link propagation. Periodic refresh, however, causes the critical impact on the protocol efficiency due to increase packet overhead in the network. To find the right refresh interval, a mobility prediction scheme [8] using GPS was proposed trying to adapt the refresh interval to nodes’ mobility. Enhanced ODMRP (E-ODMRP) [9] also eliminates overhead by dynamic adaptive route refresh and local route recovery. ODMRP-MPR [10] limits participated nodes in packet forwarding utilized the MPR technique, but packet retransmission is not restricted within MPR nodes. More nodes participate packet forwarding and passive and active acknowledge techniques are employed in order to increase reliability and delivery.

B. MIMO MAC Protocols

Even though lots of research about MIMO systems has been done recently, only a handful of MAC protocols which leverage the advantages of MIMO have been proposed.

The SPACE-MAC [2] achieves space reuse by nulling interference signals. Additional weight is applied at both a transmitter and a receiver. After applying its own weight, the transmitter emits the same signal via multiple antennas and the receiver retrieves the output by summing the weighted signals. Sender and receiver learn their weights by CTS/RTS exchanging. Other neighbors listen to the CTS/RTS exchange and adjust their own weights so as to nullify the transmitters. The neighbors are then able to start packet transmissions in the same collision domain. NULLHOC [3] approach is similar to the SPACE-MAC utilizing nulling interference signals. However, NULLHOC divides the bandwidth into two sub-channels for control and data respectively. The Mitigating Interference using Multiple Antennas MAC (MIMA-MAC) [4] eliminates interferences by nulling. It divides time into several slots, e.g., contention, training-sequence, data, and ACK slot. With divided time slots, MIMA-MAC can avoid packet collision: but, it requires all nodes in the network to be synchronized. SPACE MAC uses a single channel and requires neither time division nor synchronization.

III. PROTOCOL DESCRIPTION

A. Multi Points Relay

The purpose of the MPR is to minimize the broadcasting overhead in ad hoc network by reducing duplicated packet forwarding while guaranteeing broadcast packet delivery through out the network. It restricts the number of forwarding to a small set of neighbors, instead of all neighbors forwarding a broadcast packet like in pure flooding. The selection of the set of neighbors is completely independent of others’ selection process.

![Fig 1 Normal flooding (A) vs. MPR flooding (B)](image-url)

Each node, X, in the network designates a set of nodes, called multipoint relays (MPRs), among its one hop neighbors. Only the MPRs retransmit the packet that X broadcasted whereas other neighbor nodes process the packet without retransmission. Fig 1 (A) is the normal
broadcasting in ad hoc network. Every node retransmits received packets and total 26 transmissions occur during the broadcasting session. In Fig 1 (B), however, only MPR nodes retransmit packets so that only 8 transmissions cover all nodes in the network.

B. Creating and Maintaining the Multicast Tree

The multicast tree creation and maintenance process follows the ODMRP protocol. When a source has a packet to send, it starts broadcasting a Join Query packet periodically. Upon receiving a non-duplicated Join Query packet, a node records the upstream node address in the Routing Table to learn the reverse path. When the Join Query reaches a multicast member node, the node creates a Join Reply packet and sends it toward the source. The Join Reply packet is relayed through the learned reverse path and the nodes on the reverse path set themselves up as a “forwarding group”. After exchanging Join Query/Join Reply, the multicast tree is created and data is delivered through this multicast tree.

In the conventional ODMRP, all nodes retransmit the Join Query and thus any nodes in the network can participate in the forwarding group. Forwarding group nodes continuously relay packets as long as they do not timeout. Since forwarding group life time is much longer than the Join Query period, the multicast tree often becomes larger and larger as time goes. Through this forwarding group, ODMRP achieves multi-path and redundant packet transmissions which lead to higher delivery ratio than any other ad hoc multicast protocols. However, periodic route refresh and redundant transmissions result in high overhead which degrades protocol performance.

MIMO-CAST uses MPR nodes instead of “forwarding group” to forward packets. Only MPRs retransmit the Join Query packet and the forwarding group consists of MPRs which receive the Join Reply. Forwarding group nodes relay packets while they are MPRs. Accordingly, MIMO-CAST reduces duplicated packet transmissions and packet overhead. Low overhead in MIMO-CAST results in higher packet delivery ratio in a dense network due to decrease in contention and collision.

MIMO-CAST does not send an explicit control packet when joining or leaving the multicast group as in ODMRP. If a node wants to join the group, it waits the Join Query packet and responds by sending Join Reply. When leaving the group, a node does not respond to the Join Query. The source node simply stops sending the Join Query when it wants to leave the group.

C. MIMO-CAST MAC Protocol

Before describing the MIMO-CAST MAC protocol, we present the basic MIMO system. We assume that channels are flat fading and channel coefficients are known at the sender and the receiver. Through out this paper, we use uppercase and lowercase boldface letters to represent matrices and vectors respectively, and superscripts T and H to denote the transpose and Hermitian operations, respectively.

The first benefit of MIMO is multiplexing gain [14]. The MIMO channel can be decomposed into N parallel independent channels. The input signal from the upper layer is divided into N independent signals and delivered via multiplexing channels. Thus, the MIMO system gets an N-fold increase in data rate comparing to omni-antenna systems. The maximum number of independent signals is limited by the lesser of the number of antennas at the transmitter or the receiver. Another advantage is array and diversity gain referred to as MIMO beamforming [14].

MIMO-CAST employs the array and diversity gain to block potential interfering signal. In spite of MPR, hidden terminals still exists when a member node is placed in the overlapping area of two MPR nodes’ radio range. MIMO-CAST prevents it by employing selective reception. To applying the array and diversity gain, a receiver should know the applied weight vector of a sender. Previous MIMO MAC protocols exchange node’s weight vector using RTS/CTS. However, 802.11 MAC does not use RTS/CTS in multicast/broadcast mode. In MIMO-CAST a transmitter sends a Channel Learning (CL) packet prior to data packet transmitting to advertise own weight vector. The CL packet includes sender’s address and weight vector that will be used to send a packet. The sender waits a random delay between the CL and a data packet for receivers to adjust own weight. Upon receiving the CL packet, a node estimates channel coefficients and calculates its weight vector based on the sender’s weight vector. The weights amplify the signal from the designated sender (the parent in the MPR cluster) and nullify other signals.

Fig 2 MIMO-CAST blocks other signals
Fig 2 illustrates interference blocking in MIMO-CAST. Node S starts packet transmission and one hop neighbors adjust their weight vectors based on the CL packet. M4 cannot know S’s transmission and tries sending its packets. M3 hears M4’s CL packet and re-calculates own weight vector that enables $w_{M4}^H w_{M3} = 0$. Now M3 can receive the packet from S without interference from M4.

Another hidden terminal problem is illustrated in Fig 3. R3 is placed within the radio range of M1 and M2. M1 and M2 cannot be aware of each other’s transmissions and packet collisions may occur at R3 when two nodes transmit simultaneously. In this case, R3 selects and receives one signal arrived earlier and rejects other signals.

The MIMO system, while tuned to one transmitter, can null at most N-1 signals where N is the number of antennas. When more than N-1 signals come, the MIMO system undergoes interference.

### IV. SIMULATION RESULTS

In this section, we present simulation setup and results characterizing the performance of MIMO-CAST. We assume that the channel estimation can be done with 802.11a/b/g PLCP preamble and no error in the channel estimation. Qualnet [13] network simulator is used with default values for the configurable parameters (e.g., transmission power is 15dBm) unless otherwise specified. The channel coefficient for any transmitter and receiver antenna pairs can be modeled as an identical and independent complex Gaussian random variable.

The packet size is 1500 bytes and data rate is from 10 packets per second to 200 packets per second. 200 nodes are uniformly distributed over 1000m by 1000m area unless otherwise specified. Radio range of a node is 370m and channel capacity is 2Mbps.

For performance evaluation, we compare MIMO-CAST with MPR multicast where the MPR solution features SISO and original ODMRP. We use three metrics: Throughput = the total received byte of data packet divided by the total simulation time; Normalized Packet Overhead = the total number of packet transmissions by the network divided by the total number of data packets actually received; Average End-to-End Delay = the average time taken for a packet to be transmitted across the network from a source to a receiver; Packet Delivery Ratio = the fraction of packets received averaged over all receivers. All numbers are averaged over 10 simulation runs.

#### A. Hidden Terminal Scenario

In this experiment, we select a topology that emphasizes the hidden terminal problem.

![Fig 4 Hidden terminal topology. Node 1, 2, 3, 4 receive duplicate packets](image)

![Fig 5 Packet Delivery Ratio in hidden terminal topology](image)
compare to ODMRP and MRP multicast. In Fig 6, MIMO-CAST overhead is also the smallest among the three schemes.

B. Different Data Rate Scenarios

Next, we consider scenarios of the source transmitting data at different rates to 100 multicast group members. The source sends 1500 byte packets from 10 to 200 packets per second. Fig 7 shows that MIMO-CAST and MPR multicast throughput increase sharply whereas ODMRP throughput increases very slowly. 802.11 MAC cannot prevent the hidden terminal problem in multicast/broadcast transmission due to a lack of channel allocation scheme. In particular, ODMRP’s redundant transmissions instigate contention and collision as transmission rate escalates. MPR, however, reduces duplicated retransmission and finally achieves more throughputs thus alleviating contention and collision. With MIMO systems, the network shows better throughput by virtue of suppressing the remaining hidden terminal problems. The multiple antenna system gets at least 40 Kbyte to 550 Kbyte per second more throughput than the single antenna system.

In Fig 8, we show that MPR reduces the duplicated retransmissions. MIMO-CAST and MPR multicast send more control packets than ODMRP since they broadcast Hello packets to one hop neighbors to set up MPR nodes. However, their normalized overhead is less than a half of ODMRP’s since the MPR scheme reduces data packet forwarding. The number of data packet forwarding in MPR is less than a half compared to the ODMRP. Even though they use different number of antennas, MIMO-CAST and MPR multicast’s overhead is very close since they generate the same number of control packets at the network layer. In this simulation, MIMO-CAST normalized overhead is about 0.01 smaller than the one of MPR multicast (so we cannot distinguish in the graph).

C. Different Number of Members

In this simulation experiment, the number of multicast group members is increased to check scalability. Like the previous simulation, throughput increases as the number of group members increases. Fig 9 shows that the throughput of MIMO-CAST is 10% higher than that of MPR multicast and it more than twice that of ODMRP. Reducing duplicated retransmissions and blocking interference results in high throughput in MIMO-CAST. Normalized packet overhead also shows the same result as previous simulations. MIMO-CAST overhead is less than a half of ODMRP, and it is very close to the one of MPR multicast.

In Fig 10, we can see that MIMO-CAST end-to-end delay is very small even though it uses a pilot control message, CL packet, prior to data packet transmission. ODMRP has the longest end-to-end delay due to redundant retransmission. 802.11 MAC waits channel to be idle before transmitting a multicast/broadcast packet. Redundant forwarding occupies channel so that a node should wait long time to grab the chance to transmit the new packet. The MPR scheme reduces waiting time by suppressing duplicated retransmissions and thus the end-
to-end delay decreases. MIMO-CAST shortens end-to-end delay more than a single antenna system by channel allocation using a CL packet.

V. CONCLUSIONS

In this paper, we proposed MIMO-CAST, a cross-layer multicast MAC exploiting multiple antenna arrays. MIMO-CAST is used in conjunction with MPR. With MPR duplicated retransmission in the network can be significantly reduced. Reducing retransmission leads to a decrease in contention and collision and an increase in throughput. Hidden terminal collisions, however, still exists when a member node is placed in the overlapping area of two MPR nodes’ radio ranges. MIMO-CAST avoids this problem by employing the selective reception feature of the MIMO system. Simulation results confirm that MIMO-CAST performs far better than conventional multicast protocol with IEEE 802.11.

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