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An Efficient Cooperative Retransmission MAC Protocol for IEEE 802.11n Wireless LANs

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***Abstract*—Recently, cooperative retransmissions have exhibited great potentials in enhancing the reliability and efficiency of wireless communications by exploring spatial diversity. With cooperative retransmissions, a cooperative node helps retransmit an overheard frame if the frame from a sender fails to reach the destination. Several cooperative retransmission schemes have been proposed for wireless local area networks (WLANs) in the literature. However, most of them require explicit coordination between the sender and the cooperative node before each retransmission, which results in a non-negligible overhead. Moreover, these schemes are not designed for the latest IEEE 802.11n standard, and are incompatible with the frame aggregation and block ACK mechanisms of 802.11n. In this paper, we propose an efficient cooperative retransmission MAC (CAR-MAC) protocol that utilizes new features of 802.11n and is compatible with standard 802.11n transmissions. In CAR-MAC, all nodes periodically broadcast a C-Beacon message to release their retransmitting capability, and each node selects a cooperative node based on received C-Beacon messages. If some sub-frames in the aggregated frame from the sender fail to reach the destination, the cooperative node retransmits the failed sub-frames together with its own new sub-frames, such that overhead from cooperative retransmissions is amortized by normal frame transmissions. We have theoretically analyzed the improvement on network throughput brought by CAR-MAC protocol. In addition, we have conducted extensive simulations to evaluate CAR-MAC protocol under various channel conditions. Both theoretical and simulation results show that the proposed protocol can greatly improve network throughput and reduce packet delay, compared with the 802.11n standard and existing cooperative retransmission schemes.**

***Index Terms*—Wireless Local Area Networks (WLANs), IEEE 802.11n Standard, Cooperative Retransmission, Frame Aggregation.**

I. INTRODUCTION

In the last decade, IEEE 802.11 based wireless local area networks (WLANs) have been widely deployed to provide ubiquitous network access to laptops, tablets and smart phones. To accommodate various channel conditions, a series of physical data rates, ranging from 6.5Mbps to 600Mbps, are defined in the latest 802.11n standard [1]. In a WLAN, nodes with good channel condition transmit data frames at high data rates so as to achieve high throughput. However, WLAN performance is often limited by nodes that have low data rates, as the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism employed provisions each node an equal opportunity to access the wireless medium, regardless of its data rate [2]. In the meanwhile, nodes in WLANs use an automatic repeat request (ARQ) mechanism to ensure each data frame is successfully received by the destination. A sender expects an acknowledgment from the destination after sending a data frame. If an acknowledgment is not received, the sender retransmits the frame multiple times until an acknowledgment is received. Such retransmissions would occupy the wireless medium and intensify the contentions among nearby nodes, and thus degrade network performance. Moreover, as channel errors in WLANs tend to be in burst and temporal related, the subsequent retransmissions following an unsuccessful transmission may fail at a high probability as well. These continuous retransmission failures further deteriorate the performance of WLANs.

On the other hand, due to the broadcast nature of the wireless medium, neighbors near the sender can often successfully overhear frames that fail to reach the destination. In addition, if a neighbor instead of the sender retransmits a failed frame, the destination may receive it with a much higher probability, due to the spatial diversity of wireless medium. More importantly, the neighbor can retransmit a frame at a high data rate when the channel condition between the cooperative node and the destination is good. In this way, the network performance of an entire WLAN is significantly boosted, as the medium access time occupied by retransmissions is greatly reduced. We refer to such retransmissions by neighbors as *cooperative retransmission* in the rest of the paper.

Several cooperative retransmission schemes have been proposed in the literature. In some schemes, a preselected cooperative node helps to retransmit a frame, if the direct transmission from a sender to a destination fails. But the cooperative node may not always be the optimal one for retransmission as the wireless medium is time varying. In other schemes, multiple cooperative nodes compete to retransmit a failed frame, or retransmit a failed frame simultaneously to improve the receiving probability by the destination. However, the coordination overhead among cooperative nodes may undermine or even overwhelm the performance gain from cooperative retransmissions. Furthermore, all these schemes were designed for legacy (802.11a/b/g) WLANs, where each node transmits one frame every time, and cooperative nodes retransmit the entire frame if the direct transmission fails. While in 802.11n WLANs, a sender aggregates multiple frames into a large frame for transmission using the frame aggregation mechanism, and the destination may successfully receive some sub-frames in an aggregated frame. Then it is unnecessary and inefficient for cooperative nodes to retransmit an entire aggregated frame that has already been partially received by the destination. To the best of our knowledge, none of these schemes above have investigated how to cooperative retransmit only the failed sub-frames of aggregated frames in 802.11n WLANs.

Based on above observations, in this paper we propose a cooperative aggregated retransmission MAC (CAR-MAC) protocol for 802.11n WLANs. We first introduce a distributed scheme to dynamically select a cooperative node for each pair of sender and destination. In this scheme, all nodes periodically broadcast a *C-Beacon* message to neighbors, including overhearing capability, packet error rate, data rate for transmissions, etc. Senders choose a cooperative node for each destination based on received C-Beacon messages. In CAR-MAC protocol, a sender specifies its cooperative node explicitly when transmitting an

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aggregated frame. The selected cooperative node overhears the aggregated frame and the following block ACK frame from the destination to determine whether it is necessary to help retransmit corrupted sub-frames in the aggregated frame. The destination acknowledges an aggregated frame with a block ACK frame, including the receiving status of all sub-frames. If some sub-frames in the aggregated frame fail to reach the destination, the cooperative node aggregates the failed sub-frames into a new frame and retransmits it to the destination. The contributions of CAR-MAC are in three-fold. First, CAR-MAC takes advantage of frame aggregation and block ACK mechanisms of 802.11n for cooperative retransmissions and is fully compatible with the 802.11n standard. Second, CAR-MAC does not intensify collisions in the network, as cooperative nodes retransmits frames only after receiving a block ACK frame, which indicates that the failed sub-frames are corrupted by channel errors rather than collisions. Third, the overhead of CAR-MAC is negligible, especially in WLANs with heavy load, as cooperative nodes can aggregate retransmitting sub-frames together with their own data frames to the destination, such that the overhead of cooperative retransmissions is amortized. We theoretically analyze the improvement on network throughput brought by CAR-MAC. We also conduct extensive simulations to evaluate CAR-MAC under various channel conditions. Both numerical and simulation results show that CAR-MAC protocol can significantly improve network performance, compared with the 802.11n standard and previous cooperative retransmission schemes.

The remainder of the paper is organized as follows. Section II briefly reviews previous cooperative communication schemes for WLANs, and gives an overview of new features in the IEEE 802.11n standard. Section III describes the proposed scheme for cooperative node selection and the CAR-MAC protocol in detail. Section IV analyzes the performance of CAR-MAC theoretically. Section V provides the simulation results, followed by the conclusions in Section VI.

II. BACKGROUND AND RELATED WORK

In this section, we first review the cooperative communication schemes in the literature, including cooperative relaying schemes and cooperative retransmission schemes. After that, we give a brief overview of the new features introduced in 802.11n.

A. Cooperative Communications

Cooperative communications have exhibited great potential in improving the spectrum efficiency as well as reliability of wireless networks by exploring the broadcast nature and spatial diversity of wireless medium [3]. In [4], several cooperative strategies, including amplify-and-forward, decode-and-forward and compress-and-forward, were outlined, and the outage probabilities of these strategies were analyzed theoretically. Cooperative nodes can participate in the communication between a sender and a destination by either persistently relaying received frames to the destination, or helping retransmit a frame only if the direct transmission fails. Several cooperative relaying schemes have been presented in [5]–[8] to enhance the spectrum efficiency. However, these schemes cannot guarantee the reliability of data transmissions.

On the other hand, cooperative retransmission can improve the spectrum efficiency as well as the reliability of wireless communications. It is assumed that cooperative nodes can overhear the original transmission thus it is unnecessary to transmit the frame to the cooperative node explicitly. In some cooperative retransmission schemes, only one cooperative node is selected to help retransmit failed frames. In [9], a cooperative node is preselected for each sender-destination pair. The cooperative node retransmits the frame if an ACK timeout occurs. In the CD-MAC proposed in [10], each sender selects its cooperative node based on the received signal strength from neighbors. If the direct transmission fails, the sender and the cooperative node retransmit the frame simultaneously using the distributed space time coding (DSTC) scheme. In [11], neighbors of a sender compete to help retransmit a failed frame. Each neighbor determines its backoff duration based on the overhearing link quality and cancels its retransmission attempt after another neighbor begins retransmission. A decentralized partially observable Markov decision process (DEC-POMDP) model was given in [12] for selecting cooperative node, given imperfect channel state information.

In some cooperative retransmission schemes, multiple neighbors of the sender cooperatively retransmit a failed packet to further explore spatial diversity [13]–[15]. In [13], a cooperative group is preselected for each sender-destination pair. If a negative acknowledge is received from the destination, both the sender and all nodes in the cooperative group retransmit the packet simultaneously using DSTC. A cooperative retransmitting scheme was proposed for enhanced distributed channel access (EDCA)-enabled WLANs in [14]. In this scheme, a higher priority cooperative queue is maintained for every EDCA access class at each node. Each node caches the packets overheard from neighbors in these cooperative queues, and compete the medium to help retransmit a packet if the direct transmission fails. In [15], multiple cooperative nodes set up different retransmitting backoff durations according to their link qualities. Each cooperative node retransmits the packet when its backoff timer expires, until the packet is received by the destination. However, most diversity gains can be typically achieved with only one or two cooperative nodes. Thus the coordination overhead among multiple cooperative nodes may not be paid off by the benefits achieved.

Cooperative retransmissions can also be jointly explored with other techniques to mitigate the cooperation overhead. In [16] and [17], cooperative nodes help retransmit a frame even if they cannot fully receive the frame. The destination combines frames from both the sender and cooperative nodes to successfully decode the frame. Forward error correction (FEC) and cooperative retransmission are applied together in [18], where the cooperative nodes help calculate and transmit the parity bits of a packet gradually until the destination successfully decodes the packet. In [19], a data frame is divided into blocks and cooperative nodes help retransmit the failed blocks. However, the scheme is incompatible with the 802.11 standard and did not consider how to select and coordinate the cooperative nodes.

B. Overview of IEEE 802.11n

As the latest 802.11 standard, 802.11n has employed several new technologies to improve the speed and reliability of

WLANs. At the physical layer, multiple input multiple output (MIMO) technology is adopted to enhance the physical data rate or the reliability of WLANs by exploring either spatial multiplexing or spatial diversity. In addition, the channel boding mechanism is introduced to boost the physical data rate to more than doubled by utilizing two adjacent $20MHz$ bands simultaneously. At the MAC layer, frame aggregation and block ACK mechanisms are introduced to achieve high throughput, e.g., the maximum UDP throughput for an 802.11n transmission at 300Mbps are about 250Mbps and 40Mbps with and without these mechanisms, respectively. When frame aggregation is enabled, the sender aggregates multiple data frames into one large frame before transmitting, so as to reduce medium access overhead. After receiving an aggregated frame, the destination replies with a block ACK frame, which includes a starting sequence of the first received sub-frame and a bitmap to indicate the reception of all sub-frames in the aggregated frame. If a block ACK frame indicates that all sub-frames are successfully received, the sender prepares to transmit subsequent data units. If the block ACK indicates that the sub-frames are partially received, the sender aggregates the failed sub-frames into a new frame and transmits it when gaining the medium access next time. If a block ACK timeout occurs, the sender enters the exponential back off stages and prepares to retransmit the entire aggregated frame.

III. COOPERATIVE AGGREGATED RETRANSMISSION MAC

In this section, we present an efficient cooperative aggregated retransmission MAC (CAR-MAC) protocol for 802.11n WLANs. In CAR-MAC, each node selects only one cooperative node to help retransmit failed sub-frames if necessary. We first introduce a distributed scheme to dynamically select a cooperative node for all sender-destination pairs in the network. We then describe the CAR-MAC protocol in depth.

A. *Selection of Cooperative Nodes*

In CAR-MAC, each sender explicitly specifies a cooperative node to eliminate potential collisions among multiple cooperative retransmissions. In addition, a sender piggybacks the address of the cooperative node in the original data frame, so as to minimize the coordination overhead between the sender and the cooperative node. As shown in Fig. 1, multiple neighbors may be qualified to cooperatively retransmit failed sub-frames for a sender-destination pair at a time. However, due to the time-varying property of the wireless medium, no neighbor can always overhear the transmission from the sender and successfully deliver the retransmission. Thus, every time the neighbor that leads to the best overall network performance should be selected as the cooperative node.

Multiple factors need to be considered when selecting a cooperative node from neighbors for a sender-destination pair. We first need to consider the *overhearing ratio* of a neighbor, which is defined as the ratio of the number of sub-frames that are successfully decoded by the neighbor, to the number of sub-frames that are included in all aggregated frames overheard by the neighbor. The overhearing ratio is a good metric to evaluate the channel quality between the sender and the neighbor. Second, we should consider the *sub-frame success ratio* P_s and the *collision ratio* P_c for data transmissions from the neighbor to the destination, as they reflect the channel quality between the neighbor and the destination. The sub-frame success ratio and collision ratio are discussed separately since the former is caused by channel errors while the later comes from collisions. A neighbor of high collision probability should not be selected as the cooperative node because all cooperatively retransmitted sub-frames by such a node would fail when collision occurs. Third, the adapted data rate R from the neighbor to the destination should be considered as well because it is highly related to the efficiency of the retransmission. We also consider the channel utilization ratio U sensed by the neighbor, to avoid intensifying the contention level of a heavily loaded neighborhood. We define the aforementioned factors as the *cooperative capabilities* of a node and have each node maintain an entry for all these capabilities.

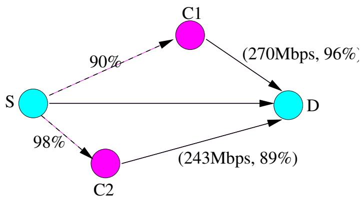


Fig. 1. An example of selecting a cooperative node for a sender-destination pair in a wireless network. S, D, C1 and C2 denote the sender, destination, candidate 1 and candidate 2 of the cooperative node, respectively. Numbers above dashed lines represent the overhearing ratio. Numbers above solid lines stand for the physical data rate and sub-frame success ratio.

In CAR-MAC, every node broadcasts a *C-Beacon* message periodically to notify the neighborhood of its cooperative capabilities. Similar to the *Beacon* message of 802.11 standard, C-Beacon is composed of information elements. The C-Beacon message has two types of information elements: *utilization element* and *cooperative neighbor element*. The utilization element includes the channel utilization ratio of the node. A node maintains a cooperative entry for each neighbor that it is willing to help retransmission. This entry includes the overhearing ratio from that neighbor, as well as the sub-frame success ratio, collision ratio and physical data rates of transmissions to that neighbor. The cooperative neighbor element for a node contains the cooperative entries of all neighbors. The overhead of C-Beacon messages is quite small for two reasons. First, C-Beacon messages are broadcast at a high data rate since they only need to reach neighbors with good channel qualities. Second, each node broadcasts a C-Beacon message every few seconds so as to reflect the change of channel conditions.

A sender determines its cooperative node based on the C-Beacon messages received from all neighbors. The neighbor that has the highest probability to successfully retransmit a message should be selected as the cooperative node. Also, as discussed earlier, nodes in a heavy traffic neighborhood should not be selected as cooperative nodes. Thus we define the rank for neighbor i as follows

$$Rank(i) = \frac{P_o(i) \cdot P_s(i) \cdot (1 - P_c(i))}{U(i)} \cdot \frac{R_i}{R_{max}} \tag{1}$$

where R_{max} is the maximum physical data rate used by all neighbors of the sender. The neighbor with the highest rank is selected as the cooperative node.

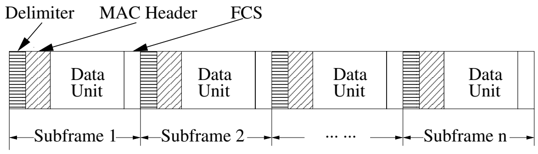


Fig. 2. Structure of an aggregated frame in 802.11n WLANs.

B. Description of CAR-MAC Protocol

In this subsection, we describe the cooperative aggregated retransmission MAC protocol in detail. In CAR-MAC, all nodes access the medium following the DCF scheme in 802.11 standard. Once obtaining the medium access, a sender aggregates multiple data packets into one large frame and transmits it to the destination. The sender also specifies the selected cooperative node in each sub-frame of the aggregated frame. The destination replies to the aggregated frame with a block ACK frame after a short inter-frame slot (SIFS) time. An overhearing neighbor caches the aggregated frame if it is the designated cooperative node; otherwise, it drops the frame after updating its overhearing ratio. If the block ACK frame implies that not all sub-frames are successfully received by the destination, the cooperative node aggregates all the failed sub-frames into a new frame, and retransmits it after a SIFS time. The destination replies to the cooperatively retransmitted frame with a *cooperative block ACK* frame. If all sub-frames retransmitted by the cooperative node are received by the destination, the sender moves on to subsequent data units. Otherwise, the sender retransmits the failed sub-frames after obtaining the medium access.

Different from most cooperative retransmission schemes in the literature, CAR-MAC does not intensify the collision level of the wireless network. First, only one cooperative node would help retransmit failed sub-frames thus there is no collision among multiple cooperative retransmissions. Second, the cooperative retransmission does not collide with the retransmission from the sender either, since the sender retransmits only if the cooperative retransmission fails and needs to compete for the medium. Third, the cooperative node will retransmit only if the transmission failure is caused by channel errors, but not by collisions. If a transmission failure is caused by channel errors, it is highly possible that the destination can still decode the MAC header of some sub-frames and then replies with a block ACK frame. In contrast, collisions often corrupt entire aggregated frames. Then both the sender and the cooperative node will observe a block ACK timeout. As the cooperative node retransmits only after receiving a block ACK, it will not help retransmit a frame corrupted by collisions.

CAR-MAC is compatible with the IEEE 802.11n standard. CAR-MAC uses the aggregated MAC protocol data unit (A-MPDU) scheme of 802.11n for frame aggregation. The data structure of an aggregated data frame is given in Fig. 2. We can see that every sub-frame in A-MPDU has its own MAC header, staring with a sub-frame delimiter. In the delimiter ahead of each sub-frame there are four reserved bits. CAR-MAC use these reserved bits to denote the cooperative type of a sub-frame. Moreover, there are four address fields in the MAC header of a sub-frame and the fourth address is unused in most scenarios. In CAR-MAC, the sender uses the fourth address field to specify the cooperative node of the aggregated frame. Moreover, the cooperative node uses this address field to specify the original sender of cooperatively retransmitted sub-frames.

2	2	6	6	2	10	4Bytes
Frame Control	Duration /ID	RA	TA	BA Control	BA Information	FCS

(a) Standard block ACK

2	2	6	6	2	10	6	10	4Bytes
Frame Control	Duration /ID	RA	TA	BA Control	BA Info	CA	Coop BA Info	FCS

(b) Cooperative block ACK

Fig. 3. Data formats of a standard block ACK and a cooperative block ACK.

To acknowledge the sub-frames retransmitted by cooperative nodes, we extend the block ACK frame of 802.11n to a cooperative block ACK frame. The data format of a standard block ACK frame is given in Fig. 3(a), in which RA denotes the MAC address of the receiver, TA denotes the MAC address of the transmitter, BA control is a 2-byte control field for block ACK, and the BA information field includes the starting sequence and the receiving bitmap of the aggregated frame. Similar to the delimiter in the aggregated frame, there are also reserved bits in the BA control field of block ACK. We extend these bits to distinguish a standard block ACK and a cooperative block ACK. In addition, we also introduce two new fields: a cooperative node address (CA) field and a cooperative information field. The format of a cooperative block ACK frame is shown in Fig. 3(b). In this way, the destination is able to simultaneously acknowledge the sub-frames of the senders retransmitted cooperatively and the new sub-frames of the cooperative node. These extensions do not alter the main structure of the aggregated frame and the block ACK frame. As a result, conventional 802.11n devices can coexist with CAR-MAC.

Cooperative retransmissions in CAR-MAC can be categorized into five cases: 1) Direct transmission succeeds; 2) Cooperative retransmission succeeds; 3) Cooperative retransmission with new sub-frames succeeds; 4) Cooperative retransmission fails; 5) Collision occurs. The data diagrams for all these cases are illustrated in Fig. 4, where S, C and D denote the sender, the cooperative node and the destination, respectively. We discuss these cases separately next.

Case 1: Both the destination and the cooperative node receive all sub-frames successfully, and the destination receives the block ACK frame. The cooperative node drops the cached sub-frames regardless whether it receives the block ACK frame or not. If a block ACK frame is received, the cooperative node knows that the destination has received all sub-frames. Otherwise, the cooperative node assumes that the destination fails to receive the aggregated frame due to collisions. As discussed earlier, the cooperative node does not retransmit cooperatively to avoid escalating the collision.

Case 2: The destination receives part of the aggregated data frame, and the cooperative node overhears all the sub-frames. In addition, both the sender and the cooperative node receive the block ACK. There is no pending traffic at the cooperative node. Thus the cooperative node aggregates and retransmits the failed sub-frames on behalf of the sender after a SIFS time. After receiving the retransmitted sub-frames, the destination replies with a cooperative block ACK frame.Both the sender and the cooperative node proceed to new transmission after receiving the cooperative block ACK frame.

Case 3: This case is similar to Case 2 except that the cooperative node also has pending traffic in its queue. To improve MAC efficiency, the cooperative node aggregates sub-frames to be retransmitted for the sender and its own new sub-frames. After receiving this mixed aggregated frame, the destination replies with a cooperative block ACK frame, acknowledging both the retransmitted sub-frames and original sub-frames from the cooperative node.

Case 4: In this case, the cooperative node also tries to retransmit failed sub-frames after receiving the block ACK frame. Nevertheless, the retransmitted frame may not be received by the destination due to channel errors or collisions. It is also possible that although all retransmitted sub-frames are received by the destination, the sender does not receive the cooperative block ACK. Since a cooperative block ACK is not received on time, the sender assumes that the cooperative node fails to retransmit the failed sub-frames. Thus the sender needs to retransmit the failed sub-frames. Note that the sender does not need to increase its contention window exponentially since the block ACK frame received earlier implies that the transmission failure is not caused by collisions.

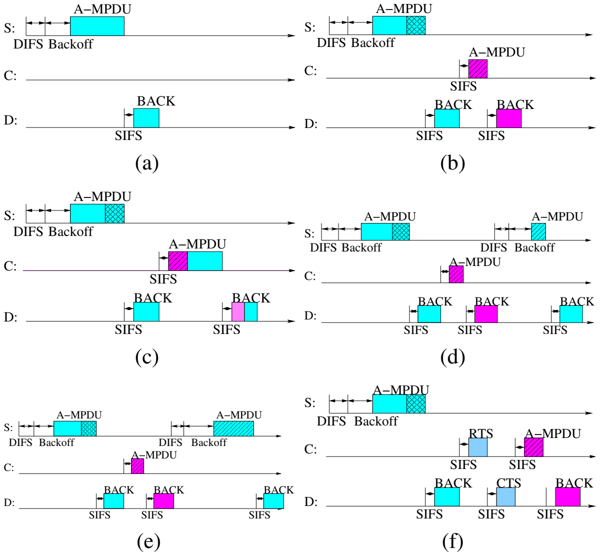
Case 5: The destination receives some sub-frames of the aggregated frame and sends back a block ACK frame. The cooperative node receives the block ACK successfully but the sender fails to receive it. Thus the cooperative node retransmits the failed sub-frames and the destination replies with a cooperative block ACK. If the sender receives the cooperative block ACK, it realizes that it has missed a block ACK and proceed to transmit new data units. Otherwise, the sender assumes that the aggregated frame is dropped due to collisions. Thus it doubles its contention window and retransmits the entire aggregated frame after obtaining medium access.

To avoid being collided by potential hidden terminals, the cooperative node may exchange RTS/CTS control frames with the destination before cooperative retransmissions. As shown in Fig. 4(f), the cooperative node sends a RTS frame to the destination after a SIFS time from the block ACK frame, while the destination node replies to the RTS frame with a CTS frame. After that, the cooperative node retransmits the sub-frames as specified by CAR-MAC. Note that no modification to the RTS/CTS mechanism is needed.

From the above descriptions, we can see that CAR-MAC is simple but efficient in retransmitting failed sub-frames cooperatively. It is also robust to various error conditions since no complex state transition is introduced at the sender and the cooperative node. Note that cooperative nodes can adapt the ratio of cooperatively retransmitting traffic and their own traffic by dynamically adjusting the maximal number of retransmitting sub-frames in an aggregated frame. However, the topic is out of the scope of this paper and will be investigated in our future work.

IV. PERFORMANCE ANALYSIS

In this section, we analyze the performance of the proposed CAR-MAC protocol and compare it with the standard 802.11n transmissions. We will first derive the approximate throughput of CAR-MAC on independent and identically distributed (i.i.d.) channels based on a Markov model. We will also give numerical results about the improvement on network throughput by CAR-MAC.



(a) (b) (c) (d) (e) (f)

Fig. 4. Various cases of cooperative retransmissions in CAR-MAC, where S, C and D denote the sender, cooperative node and the destination, respectively. Pink blocks represent cooperatively retransmitted sub-frames and cooperative block ACK, while blue blocks represent direct transmission and block ACK. (a) Case 1: Direct transmission succeeds. (b) Case 2: Cooperative retransmission succeeds. (c) Case 3: Cooperative retransmission with new sub-frames succeeds. (d) Case 4: Cooperative retransmission fails. (e) Case 5: Collision occurs. (f) RTS/CTS protects cooperative retransmission.

A. Throughput Analysis of CAR-MAC

In this subsection, we model the throughput of CAR-MAC using a bi-dimensional Markov model. A Markov model was proposed in [20] for conventional multi-rate WLANs, where nodes may have different traffic loads, physical data rates and payload sizes. However, in this model, transmission failures caused by channel errors cannot be distinguished from failures resulted from collisions, making it inapplicable to CAR-MAC. We extend this model to support the frame aggregation and block ACK features of 802.11n to describe the throughput of CAR-MAC. For simplicity, we assume all nodes are within the carrier sense range of each other and there is no hidden terminal in the network. Based on this assumption, the contention behavior of CAR-MAC is identical to the MAC protocol of 802.11n. This is because that both the cooperative retransmission frame and cooperative block ACK frame introduced in CAR-MAC are transmitted after a SIFS interval from the block ACK frame, making it unnecessary to compete for the medium before transmitting them. Thus they have no impact on the contention behavior of the WLAN.

According to the Markov model, every node in the WLAN has a stationary transmission probability and a stationary collision probability. We further assume that all nodes in the WLAN always have pending traffic to transmit. Hence the transmission probabilities and the collision probabilities of all nodes are identical to each other. Using the chain transition probability given in [20], the transmission probability τ for a node can be expressed as

$$\tau = \frac{2(1-2P_c)}{(1-2P_c)(W_0+1)+P_cW_0(1-(2P_c)^m)} \tag{2}$$

where P_c, W_0 and m stand for the collision probability, the initial contention window size and the number of back off stages, respectively.

Let the number of nodes in the WLAN be N, then the collision probability for a transmitting node is equivalent to the probability that as least another node transmits simultaneously, that is,

$$P_c = 1 - (1-\tau)^{N-1} \tag{3}$$

For an aggregated frame transmitted by any node i, we assume that the channel errors for all sub-frames satisfy independent and identical distribution and define the sub-frame error probability as $P_e(i)$. Then the transmission of an aggregated frame can be described as a series of Bernoulli trials. We further define the average aggregation level for node i as $A(i)$. Therefore, when no collision occurs, the expected number of successfully received sub-frames $E^D_{avg}(i)$ for a direct transmission is

$$E^D_{avg}(i) = A(i) \cdot (1 - P_e(i)) \tag{4}$$

On the other hand, in CAR-MAC the cooperative node retransmits all failed sub-frames caused by channel errors. It is reasonable to assume that these retransmitted sub-frames can also be described as a series of Bernoulli trials. We denote the sub-frame error probability for the cooperative node of sender i as $P^C_e(i)$. Then the expected number of received sub-frames $E^C_{avg}(i)$ for a transmission with cooperative retransmission is equivalent to the summation of the number of sub-frames delivered by the sender and the number of sub-frames delivered by the cooperative node, that is,

$$E^C_{avg}(i) = E^D_{avg}(i) + (A(i) - E^D_{avg}(i)) \cdot (1 - P^C_e(i)) \tag{5}$$

If cooperative retransmission is not adopted, the theoretical throughput for node i can be expressed as the length of successfully delivered payload from the direct transmission divided by the average duration of a time slot T^D_{avg} for all nodes in the network. Thus throughput $S^D(i)$ for node i can be represented as

$$S^D(i) = \frac{(1-P_c) \cdot E^D_{avg}(i) \cdot L}{T^D_{avg}} \tag{6}$$

where L is the average length of a sub-frame.

Similarly, the theoretical throughput $S^C(i)$ for node i in CAR-MAC can be defined as the length of payload delivered by both the sender and the cooperative node, divided by the average duration of a time slot for all nodes in CAR-MAC

$$S^C(i) = \frac{(1-P_c) \cdot E^C_{avg}(i) \cdot L}{T^C_{avg}} \tag{7}$$

The average time slot duration for both CAR-MAC and standard 802.11n MAC can be further expressed as the summation of four expected time slots

$$T_{avg} = T_{idle} + T_{succ} + T_{col} + T_{error} \tag{8}$$

where T_{idle}, T_{succ}, T_{col} and T_{error} stand for the expected durations of an idle time slot, an aggregated frame that is fully received, a transmission failure due to collisions and an aggregated frame in which some sub-frames are corrupted by channel errors, respectively. As aforementioned, CAR-MAC does not affect the collision probability and transmission probability of nodes. Thus T_{idle} of CAR-MAC equals the T_{idle} of standard 802.11n MAC. Moreover, as the cooperative node does not retransmit in cases of successful transmissions and collisions, the T_{succ} and T_{col} of CAR-MAC are also identical to those of standard 802.11n MAC.

The expected duration of an idle time slot can be defined as the product of the probability that no node is transmitting and the duration of a back off time slot, that is,

$$T_{idle} = (1-\tau)^N \cdot \delta$$

where δ denotes the duration of a back off time slot.

The duration of a successful transmission includes a DIFS interval, the time needed to transmit the aggregated frame, a SIFS interval and the time to transmit the block ACK frame. The time of the aggregated frame can be further divided into two parts: physical layer convergence protocol (PLCP) header and the transmission of the data payload. Moreover, the transmission time of the data payload is related to the aggregation level and the physical data rate. Putting all these together, the duration $T_{succ}(i)$ of a successful transmission for node i can be formally expressed as

$$T_{succ}(i) = T_{difs} + T_{sifs} + T_{plcp} + T_{back} + \frac{A(i) \cdot L}{R(i)}$$

in which T_{difs}, T_{sifs}, T_{plcp}, T_{back} and $R(i)$ represent the DIFS interval, the SIFS interval, the duration for a PLCP header, the duration of a block ACK frame and the physical data rate for node i, respectively.

Accordingly, the expected duration of a successful transmission in the WLAN is equal to the summation of the products of successful transmission probability and transmission duration for all nodes. The successful transmission probability for node i can be rewritten as the probability that only node i transmits and all sub-frames are successfully received. Thus T_{succ} can be given by

$$T_{succ} = \sum_{i=1}^{N} \tau(1-\tau)^{N-1}(1-P_e(i))^{A(i)} \cdot T_{succ}(i)$$

For standard 802.11n MAC, the duration of an erroneous transmission is the same as that of a successful transmission, since they are both acknowledged by a block ACK frame. We define $T^D_{error}(i)$ as the duration of an erroneous frame without cooperative retransmission for node i, thus

$$T^D_{error}(i) = T_{succ}(i)$$

For CAR-MAC, besides all the time components in $T^D_{error}(i)$, the duration of an erroneous transmission also includes the cooperative retransmitted frame, the cooperative block ACK and the two SIFS intervals between these frames. Thus, the duration of an erroneous transmission for node i in CAR-MAC, $T^C_{error}(i)$, is given as follows

$$\begin{aligned} T^C_{error}(i) &= T^D_{error}(i) + 2T_{sifs} \\ &+ T_{back} + T_{plcp} + \frac{(E^C_{avg}(i) - E^D_{avg}(i))L}{R^C(i)} \end{aligned}$$

Similar to the expected duration of successful transmissions, the expected duration of erroneous transmissions can be represented as the summation of the products of erroneous transmission probability due to channel error and $T_{error}(i)$ for all nodes. The erroneous transmission probability for node i equals the probability that only node i transmits and at least one sub-frame is corrupted. Then the expected duration T^D_{error} for erroneous transmissions in standard 802.11n and the expected duration T^C_{error} for erroneous transmissions in CAR-MAC can be expressed as

$$\begin{aligned} T^D_{error} &= \sum_{i=1}^{N} \tau(1-\tau)^{N-1}(1-(1-P_e(i))^{A(i)})T^D_{error}(i) \\ T^C_{error} &= \sum_{i=1}^{N} \tau(1-\tau)^{N-1}(1-(1-P_e(i))^{A(i)})T^C_{error}(i) \end{aligned} \tag{9}$$

A collision is detected if a block ACK timeout occurs. Thus the time for node i to detect a collision is

$$T_{col}(i) = T_{difs} + T_{plcp} + T_{backtimeout} + \frac{A(i) \cdot L}{R(i)}$$

where $T_{backtimeout}$ is the duration for a block ACK timeout.

If collision occurs between two transmissions that are of different transmission times, the wireless medium would be occupied by the longer transmission. To determine the expected duration of a collision for all nodes in the WLAN, we first sort all nodes in an ascending order of their collision detection time $T_{col}(i)$. We then assume that node i collides only with other nodes that have a shorter transmission duration. In this way, the collision between any two nodes i and j, ($T_{col}(i) < T_{col}(j)$), will be only counted by node j, rather than by both of them, when we calculate the expected collision duration of the network. Then the collision probability for node i can be rewritten as

$$P_{col}(i') = (1-(1-\tau)^{i'-1}) \cdot \tau \cdot (1-\tau)^{N-i'}$$

where $i'(1 \leq i' \leq N)$ is the index of node i in the sorted list of all nodes.

Consequently, the expected duration of collision for all nodes is

$$T_{col} = \sum_{i'=1}^{N} P_c(i')T_{col}(i')$$

By plugging Equations (4), (8) and (9) into Equation (6), the throughput for node i in standard 802.11n networks is

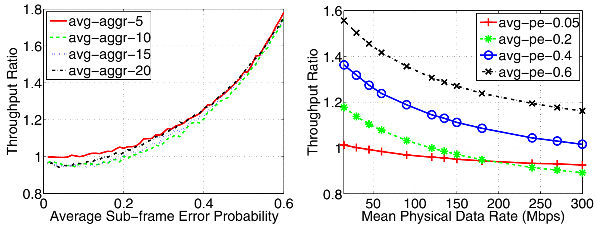
$$S^D(i) = \frac{(1-P_c)(1-P_e(i)) \cdot A(i) \cdot L}{T_{idle} + T_{succ} + T_{col} + T^D_{error}} \tag{10}$$

Similarly, by plugging Equations (5), (8) and (9) into Equation (7), the throughput for node i in CAR-MAC is

$$S^C(i) = \frac{(1-P_c)(1-P_e(i) \cdot P^C_e(i)) \cdot A(i) \cdot L}{T_{idle} + T_{succ} + T_{col} + T^C_{error}} \tag{11}$$

B. Numerical Results for an Example WLAN

We now apply the above theoretical analysis to an example WLAN. We evaluate the overall network throughput of CAR-MAC and compare it with standard 802.11n transmissions. Consider a 10-node WLAN where all nodes are of saturated traffic. All parameters used in the calculation are taken from the specification of 802.11n. By plugging these parameters into the equations given in the last subsection, we can derive the throughput of each node for both CAR-MAC and standard 802.11n. As both the sub-frame error probability and the physical data rate for cooperative retransmissions are considered when selecting cooperative nodes, we will discuss the impact of these two factors separately. We define *throughput ratio* as the ratio of network throughput of CAR-MAC to the network throughput of standard 802.11n transmission, to show the superior of CAR-MAC in boosting network throughput.



(a) (b)

Fig. 5. Aggregated throughput ratio of CAR-MAC to standard 802.11n transmissions in an example WLAN. (a) Throughput ratio under different sub-frame error probabilities. (b) Throughput ratio under different physical data rates at the sender.

We first study the performance of CAR-MAC in terms of throughput ratio under different sub-frame error probabilities. All cooperative nodes retransmit at the same data rate as the sender in this case. In addition, the sub-frame error probability for all senders is a random variable with expected value $E(P_e)$ and the sub-frame error probability for all cooperative nodes is also a random variable with expected value $E(P^C_e)$. We fix $E(P^C_e)$ at 0.05 and increase $E(P_e)$ from 0.05 to 0.6. The numerical results for these configurations are plotted in Fig. 5(a), where the throughput ratio of average aggregation levels 5, 10, 15 and 20 are plotted separately. We can see that as $E(P_e)$ grows, the benefits of cooperative retransmissions become more significant. Specifically, when $E(P_e)$ equals 0.5, the network throughput is improved over 50% by CAR-MAC compared with standard 802.11n transmissions. We can also observe that the effects of CAR-MAC are more obvious when the expected aggregation level is low. This is reasonable because the network throughput of direct transmissions grows linearly with the aggregation level, but the number of sub-frames that need retransmission increases much slowly when the sub-frame error probability is small. Note that the gap of throughput ratios among different aggregation levels decreases as $E(P_e)$ increases.

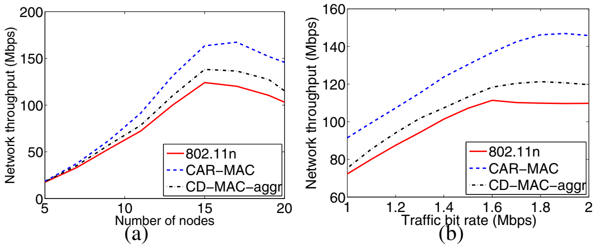
We also examine the performance of CAR-MAC when the cooperative node is capable of retransmitting failed sub-frames at a higher data rate than the original sender. We assume that every cooperative node and the corresponding sender have the same sub-frame error probability. We set the physical data rate for all cooperative retransmissions to be $300Mbps$, while increasing the physical data rate of direct transmissions from $15Mbps$ to $300Mbps$. The numerical results are given in Fig. 5(b), where the scenarios of average sub-frame error probability being 0.05, 0.2, 0.4 and 0.6 are examined separately. We can note that when the difference of transmitting data rate between the senders and the cooperative nodes is larger, CAR-MAC has more benefits. The reason is that if a cooperative node has the same transmitting data rate and the same sub-frame error probability as the sender, cooperative retransmissions will have the same MAC efficiency as direct transmissions. We can also see that when the sub-frame error probability is 0.05, the network throughput of CAR-MAC is slightly lower than standard 802.11 transmissions. This is because that only few sub-frames need to be retransmitted in such situations, where the gain of retransmissions cannot cover the overhead. Fortunately, such performance degradation can be avoided in CAR-MAC since it allows the cooperative node to aggregate its own data units with cooperatively retransmitted sub-frames, so as to ensure high MAC efficiency.

V. SIMULATION RESULTS

In previous section, we have shown that CAR-MAC can greatly boost the throughput of a WLAN, by assuming that cooperative nodes have either better sub-frame error probabilities or higher transmitting data rates than senders. But in real WLANs, it cannot be guaranteed that cooperative nodes always have better channel conditions than senders. Moreover, the overhead of selecting cooperative node is not discussed. In this section, we will thoroughly evaluate the performance of CAR-MAC under various network scenarios in terms of network throughput and packet delay via simulations. We will also explore the impact of C-Beacon messages on network throughput. As discussed earlier, 802.11n WLANs achieve high throughput by using frame aggregation and block ACK, which were not supported by existing cooperative retransmission schemes. Therefore, we will compare CAR-MAC with standard 802.11n transmissions, and a CD-MAC [10] like scheme, named *CD-MAC-aggr*, in which the cooperative node retransmits an entire aggregated frame if the frame is not fully received by the destination.

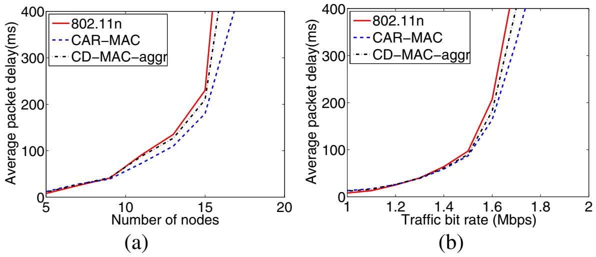
In the simulation, the WLAN is deployed over a $200 \times 200m^2$ field. All nodes are stationary and transmit at the maximum power level such that they can sense the transmission of each other, so as to avoid hidden terminal problems. In addition, all nodes operate in an ad hoc mode thus direct transmission between any two nodes is permitted. An optimal data rate is selected for each pair of nodes by taking their distance into the Ricean fading propagation model. Rate adaptation is disabled in the simulation, as sub-frame error probability can be affected by the employed rate adaptation algorithm. Each node sends constant bit rate (CBR) UDP traffic to all other nodes. If not otherwise specified, all nodes broadcast a C-Beacon frame every second. In addition, the traffic bit rate of each flow is set to 1Mbps.

We first examine the network throughput of CAR-MAC under various node densities. The simulation results are plotted in Fig. 6(a), where the number of nodes increases from 5 to 20 in a step of 2. It is noted that CAR-MAC always has higher network throughput than the compared schemes, regardless of the node density. Moreover, the advantage of CAR-MAC is more evident when the node density is high. In particular, the network throughput of CAR-MAC is 39% and 27% higher than 802.11n transmissions and CD-MAC-aggr respectively, when the number of nodes is 20. This is because in CAR-MAC cooperative nodes retransmit frames more efficiently than senders, and they only retransmit failed sub-frames instead of entire aggregated frames. For similar reasons, it can also be observed from Fig. 6(b) that CAR-MAC always leads to the highest network throughput under various traffic loads, where the number of nodes is fixed at 10 and the traffic load on each flow changes from 1Mbps to 2Mbps. It should be pointed out that the network throughput of all schemes begins to decrease when the number of nodes or the traffic load grows beyond a threshold, which can be attributed to collision penalty in a saturated network. Nevertheless, the turning point of CAR-MAC appears later than the compared schemes in both Fig. 6 (a) and (b), indicating that CAR-MAC is more beneficial in saturated networks.



(a) (b)

Fig. 6. Network throughput of CAR-MAC under various node densities and traffic loads. (a) Network throughput vs. Number of nodes. (b) Network throughput vs. Traffic bit rate for each flow.

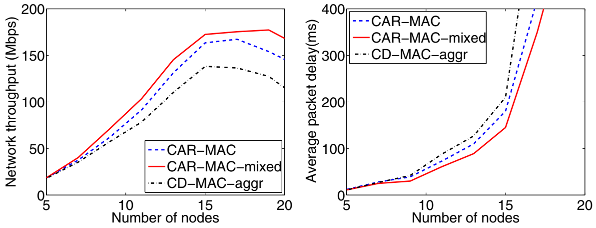


(a) (b)

Fig. 7. Average packet delay for CAR-MAC under various node densities and traffic loads. (a) Average packet delay vs. Number of nodes. (b) Average packet delay vs. Traffic bit rate for each flow.

We now study the average packet delay of CAR-MAC in WLANs with different number of nodes and various traffic loads. Fig. 7 shows the simulation results. We can see that when the number of nodes is small or the traffic load is light, the packet delay of all schemes is low as most packets are transmitted immediately rather than queued when they arrive at the MAC layer. As the node density or traffic load increases, the average packet delay of CAR-MAC grows more slowly than standard 802.11n transmissions. The reason is that CAR-MAC is able to reduce the number of retransmissions for failed sub-frames, so as to decrease their packet delay. Moreover, the packet delay of following packets in the queue is also shortened as the time occupied by retransmissions is reduced. We can also observe that CAR-MAC has a shorter packet delay than CD-MAC-aggr, because CD-MAC-aggr takes extra time to retransmit sub-frames that have already been successfully received. Note that the average packet delay increases drastically when the traffic in the network is saturated, as the data queues will overflow eventually and thus a large number of packets are dropped.

We also investigate the gains of aggregating the cooperatively retransmitted sub-frames together with new data units at the cooperative nodes. Fig. 8 gives the network throughput and the average packet delay of all nodes, in which CAR-MAC-mixed represents the strategy of mixing retransmitted sub-frames with new data units. From Fig. 8(a) we can observe that when the number of nodes is small, the network throughput of the



(a) (b)

Fig. 8. Benefit of aggregating new data units together with cooperative retransmitted sub-frames in CAR-MAC. (a) Improvement in network throughput. (b) Reduction in average packet delay.

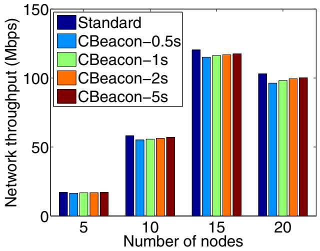


Fig. 9. Impact of C-Beacon messages on standard 802.11n transmissions.

mixed strategy is close to that of the basic CAR-MAC. This can be attributed to the fact that the overhead of cooperative retransmissions is not reflected in the network throughput when the network load is unsaturated. When the number of nodes is large, the advantage of the mixed strategy is remarkable, indicating its capability of amortizing the overhead of cooperative retransmissions as well as alleviating contention intensity. The relatively low packet delay exhibited in Fig. 8(b) also verifies that the mixed strategy is capable of utilizing the wireless spectrum more efficiently.

Finally, we evaluate the impact of C-Beacon messages on the network throughout of normal 802.11n transmissions. Cooperative retransmissions are disabled in this case to exclude the throughput gain of cooperative retransmissions. The network throughput for standard 802.11n WLANs with C-Beacon messages is plotted in Fig. 9, where Standard, CBeacon-0.5s, CBeacon-1s, CBeacon-2s and CBeacon-5s stand for the scenarios that WLAN nodes do not broadcast C-Beacon messages, and broadcast a C-Beacon message every $0.5s$, $1s$, $2s$ and $5s$, respectively. We can see that the impact of C-Beacon messages on the overall network throughput is very limited, even when C-Beacon messages are broadcast every $0.5s$ and the network is under severe contention. This is because that C-Beacon messages are generated at a much lower frequency compared with the heavy data traffic. In addition, as C-Beacon messages are small packets broadcast at high data rates, they occupy the wireless medium for very short durations. More importantly, similarly to Beacon messages, C-Beacon messages are buffered at a separate queue at each node, which has higher medium access priority than the data queues. Therefore, they will not escalate the contention level of a network, as they can always obtain the medium without causing a physical collision when competing with data frames.

VI. CONCLUSIONS

In this paper, we have proposed a cooperative retransmission MAC (CAR-MAC) protocol for IEEE 802.11n based WLANs, taking full advantage of frame aggregation and block ACK mechanisms of 802.11n. We first gave a distributed scheme to select cooperative nodes, such that each node may dynamically select a cooperative node for each destination. We then presented the CAR-MAC protocol in which the cooperative node only retransmits the failed sub-frames caused by channel errors. After that, we analyzed the theoretical throughput of the proposed protocol and derived numerical results based on the analysis. Finally, we conducted extensive simulations to evaluate the performance of the proposed protocol. Both numerical and simulation results show that the propose protocol boosts the network throughput and reduces the average packet delay significantly. In our future work, we will further evaluate the proposed protocol by implementing it in a real-world testbed. In addition, we will study the fairness among direct transmissions and cooperative retransmissions in CAR-MAC.

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