Cooperative Communication Protocol based on Relay Node Grouping in Wireless Networks

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Abstract

IEEE 802.11a/b/g standards support multiple data rates. Although the use of multiple data rates increases the capacity of wireless networks, it can lead to a performance anomaly problem. Cooperative communication for wireless networks has attracted considerable interest owing to its ability to mitigate this performance anomaly problem. In cooperative communication, a number of relay nodes support a source node in the forwarding of data packets to a destination node. If the direct transmission of a data packet between a source node and a destination node is not successful, the overheard data packet from the source node is forwarded by relay nodes to the destination node. Several MAC (Medium Access Control) protocols have been proposed for cooperative communication in wireless networks. A number of these can result in collisions among the relay nodes in a dense network. Further, cooperative communication can be interrupted by other nodes. To resolve these problems, we propose a new cooperative protocol. In the proposed protocol, relay nodes are divided into several groups based on their data rates. Then, to limit the number of contending relay nodes, only the relay nodes in the highest group are selected. Collisions among the selected relay nodes are resolved based on a backoff mechanism. The proposed protocol ensures that cooperative communication is not interrupted by other nodes by implementing a busy signal and NAV (Network Allocation Vector). The proposed protocol can reduce the collision probability and increase the network performance. Performance evaluation is conducted using simulation, and confirms that the proposed protocol significantly outperforms the previous protocol in terms of throughput, collision probability, and delay.

Keyword-Cooperative communication, MAC protocol, Relay node grouping, WLAN

I. INTRODUCTION

The IEEE 802.11 wireless LAN is widely used for wireless access due to its easy deployment and low cost. The IEEE 802.11 standard defines a medium access control (MAC) protocol for sharing the channel among nodes [1]. A distributed coordination function (DCF) was designed for contention-based channel access. The DCF has two data transmission methods: the default basic access and optional RTS/CTS (request-to-send/clear-to-send) access. The basic access method uses a two-way handshaking (DATA-ACK) mechanism. The RTS/CTS access method uses a four-way handshaking (RTS-CTS-DATA-ACK) mechanism to reserve the channel before transmitting long data packets. This technique is introduced to avoid the hidden terminal problem.

IEEE 802.11 DCF is essentially carrier sense multiple access with collision avoidance (CSMA/CA). Packet collisions on the medium are resolved using a binary exponential backoff algorithm. A node with a data packet to transmit ensures that the medium is idle before attempting to transmit. It selects a random backoff counter less than the current contention window based on a uniform distribution and then decreases the backoff counter by one at each slot when the medium is idle. If the medium is busy, the node defers until the end of the current transmission. The node transmits a data packet when its backoff counter reaches zero.

The most fundamental method available to enhance the capacity of wireless LANs is providing a higher data rate at the physical layer. IEEE 802.11a/b/g were standardized to expand a physical layer capable of offering higher data rates. These standards provide multiple data rates, which can be changed dynamically according to the channel condition.

Cooperative communication was introduced to improve the overall performance of wireless LANs with the support of relay nodes with higher data rates [2]. Cooperative communication is based on the fact that transmission is significantly faster when sending data packets to a destination node through a relay node with a higher data rate, rather than sending data directly to the destination node at a low data rate. To apply cooperative communication in wireless LANs, several MAC protocols have been proposed [2]-[16].

Previous cooperative MAC protocols are classified into two categories: proactive cooperation communication and distributed cooperative ARQ communication [3]. Distributed cooperative ARQ communication exploits the broadcast nature of the wireless channel [3]-[10]. A source node transmits its own data packet to a destination node directly (i.e., direct transmission). This operation is the same as the DCF in wireless LANs. When the destination node receives an erroneous data packet from the source node, it requests retransmissions from any of the relay nodes that overheard the original data packet from the source node. The relay nodes in the network are enabled to forward the original packet to the destination node.

In Persistent Relay Carrier Sensing Multiple Access (PRCSMA), a node stores all the received data packets in its own temporary buffer to act as a relay node when required [4]. When the communication between a source node and a destination node fails, cooperative communication begins. The destination node sends a claim for cooperation (CFC) packet when it receives an erroneous data packet. Nodes, which correctly received both the data packet from the source node and the CFC packet from the destination node, operate as relay nodes. The relay nodes attempt to send the data packet to the destination node based on the backoff mechanism, which is similar to DCF. This procedure is repeated until the destination node successfully receives the data packet. The PRCSMA protocol can result in long delays and low bandwidth efficiency because of channel contention among the relay nodes. Further, the protocol has a problem in that cooperative communication can be interrupted by other nodes in the network during channel contention among the relay nodes.

The cooperative ARQ (C-ARQ) protocol was proposed to resolve the problems in the PRCSMA protocol [3], [5]. The C-ARQ protocol also sends a CFC packet when a destination node receives an erroneous data packet. Relay nodes measure the signal-to-noise ratio (SNR) between themselves and the destination node. Then, they determine their backoff times based on the measured SNR to avoid collisions among themselves. The backoff counter time is less than the DIFS (DCF Inter-Frame Space) interval.

In proactive cooperation communication, a source node determines the method to transmit its own data packet (either source-destination direct communication or source-relay-destination cooperative communication) based on the channel condition [2], [11]-[16]. When the channel between the relay node and the destination node is superior to the channel between the source node and the destination node, cooperative communication is selected instead of direct communication. In the CoopMAC protocol [2], each node maintains a table that has information such as data rates among nodes. When there are data packets to send, a source node selects a node with the least packet transmission time as a relay node. Then, the source node sends a CoopRTS packet to the relay node. The relay node checks whether it can provide the service. If it can, the relay node sends an HTS (Helper ready To Send) packet. The destination node sends a CTS packet to the source node. After receiving the CTS packet, the source node sends a data packet to the relay node, which then forwards the data packet to the destination node.

The rDCF protocol [11] is a similar concept to the CoopMAC protocol. The main difference between them is the method to update the table. In the CoopMAC protocol, nodes estimate the data rate based on the received signal strength of the packets. In the rDCF protocol, nodes extract the data rate in the CTS packet.

The focus of this paper is on the design of a MAC protocol based on distributed cooperative ARQ communication. The C-ARQ protocol continues to have several problems. To resolve these problems, we propose a new protocol, called RNG-MAC (Relay Node Grouping MAC) protocol. In the proposed protocol, relay nodes are divided into several groups based on their data rates. Then, to limit the number of channel contending relay nodes, only the relay nodes in the highest group are selected. Therefore, the proposed protocol can reduce the collision probability among the relay nodes and improve the performance of the network.

This paper is organized as follows. In Section II, we provide a brief introduction to the C-ARQ protocol and present the motivation for our work. In Section III, the proposed RNG-MAC protocol is presented in detail. In Section IV, performance studies are performed with simulation results. Finally, we conclude this paper in Section V.

II. Related Work

In this section, we summarize the C-ARQ protocol proposed in [3], [5] and then present the motivation for our work by identifying the limitations of the C-ARQ protocol.

The C-ARQ protocol consists of two phases: direct and cooperative communication. The cooperative communication is initiated if the direct communication fails. The direct communication is based on DCF basic access. When a source node (S) has a data packet to transmit, it selects a random backoff counter. If the channel is free for the DIFS interval, the source node decreases its backoff counter while the channel is idle. The source node transmits the data packet to a destination node (D) when its backoff counter reaches zero. When the destination node receives the data packet without an error, it transmits an ACK packet to the source node after the SIFS (Short Inter-Frame Space) interval. This procedure is called a direct communication. Fig. 1 illustrates an example of direct communication.

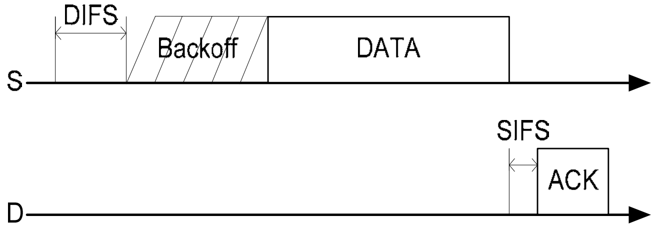

Fig. 1. Example of the direct communication

If the destination node receives the data packet with error, then cooperative communication is initiated. The destination node transmits a CFC packet to request a set of retransmissions from any of the relay nodes that have successfully received data packet from the source node. A relay node i selects its own backoff time (Ti) to avoid channel collision among the relay nodes as follows:

$$T_i = \left\lfloor \frac{SNR_{low}}{SNR_i} \times \frac{DIFS - SIFS}{aSlotTime} \right\rfloor \quad (1)$$

where SNR_i is the SNR value in dB of the CFC packet, SNR_{low} is the threshold to participate in the cooperative communication, and *aSlotTime* is the duration of a slot time. The upper bound of the backoff time for relay nodes is designed to be (*DIFS* - *SIFS*) to guarantee that the cooperative communication is not interrupted by other nodes in the network.

If the channel is free for the SIFS interval, each relay node decreases its backoff time while the channel is idle. A relay node forwards the original data packet to the destination node when its backoff time reaches zero. The destination node sends an ACK packet after receiving the data packet without an error.

Fig. 2 presents an example of cooperative communication. In this example, there are four nodes: source node (S), destination node (D), and relay nodes (R1 and R2). The backoff time for R1 is shorter than that for R2. Therefore, R1 transmits the received data packet and R2 withdraws from the cooperation contention and discards the received data packet.

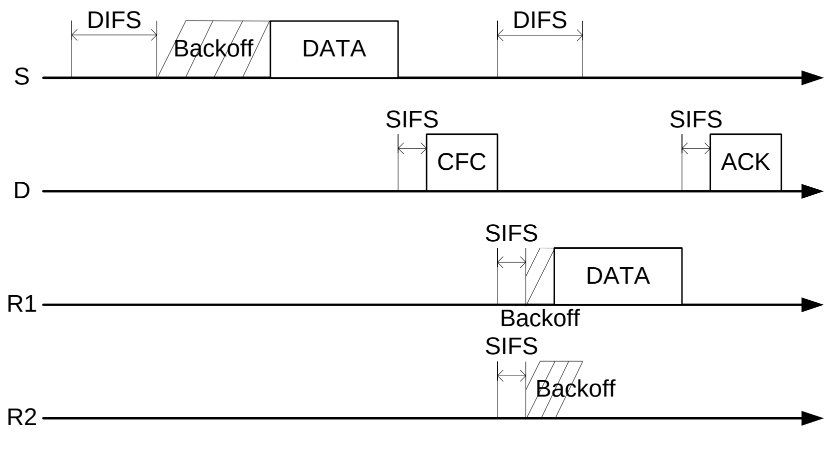

Fig. 2. Example of the cooperative communication in C-ARQ protocol

The C-ARQ protocol does have a problem. The upper bound of the backoff time for relay nodes is (*DIFS* - *SIFS*). The IEEE 802.11 standard defines *DIFS* = *SIFS* + (2 * *aSlotTime*). Therefore, the C-ARQ protocol can distinguish at most $\left\lfloor \frac{DIFS - SIFS}{aSlotTime} \right\rfloor$ (= 2) relays. This can result in high collisions among relay nodes in a dense network. To solve this problem, the EB.C-ARQ (Extended Backoff C-ARQ) protocol was proposed by the same authors [3]. In the EB.C-ARQ protocol, the upper bound of the backoff time is extended to (*DIFS* – *SIFS* + *CWmin* * *aSlotTime*). *CWmin* is the minimum contention window. In this manner, more relay nodes can be distinguished. However, this does not guarantee anything more than the fact that cooperative communications is not interrupted by other nodes. If there are no relay nodes between the source node and the destination node, the source node must wait for the (*DIFS* – *SIFS* + *CWmin* * *aSlotTime*) time. Therefore, it can waste channel time. In the C-ARQ and EB.C-ARQ protocols, all the relay nodes that receive the data and CFC packets attempt to forward the data packet even though their data rates are lower than that of the source node. Consequently, it can result in reduce network performance.

III. RNG-MAC PROTOCOL

In the C-ARQ protocol, all the relay nodes attempt to obtain channel access to forward the received data packets. In the EB.C-ARQ protocol, cooperative communication is interrupted by other nodes and may waste channel time. Therefore, these protocols have high collision probability and low network performance. To resolve these problems, we propose the RNG-MAC protocol. The proposed RNG-MAC protocol is similar to the C-ARQ protocol. However, in the proposed protocol, relay nodes are divided into several groups based on their data rates. Then, only the relay nodes in the highest group attempt to obtain channel access. Further, the proposed protocol ensures that cooperative communication is not interrupted by other nodes and does not waste channel time by implementing a busy signal and NAV (Network Allocation Vector). Therefore, the proposed protocol can reduce the collision probability and increase the network performance.

The proposed RNG-MAC protocol is composed of direct and cooperative communication. It first initiates direct communication. This is similar to the operation of the C-ARQ protocol. When a source node has a data packet, it transmits the data packet to the destination node if its own backoff timer expires. The destination node transmits an ACK packet to the source node if it successfully receives the data packet. Otherwise, cooperative communication begins for delivering the data packet. Cooperative communication consists of four phases: start phase, awareness phase, group selection phase, and data-forwarding phase. In the start phase, the destination node notifies nodes in the network of the start of the cooperative communication. In the awareness phase, each node determines if it can be a relay node. If there are relay nodes, every node is aware of the existence of the relay nodes. In the group selection phase, every relay node determines its own group based on data rate, and the relay nodes in the highest group are selected. In the data forwarding phase, the collisions are resolved among the selected relay nodes using a backoff mechanism and the original data packet is forwarded to the destination node.

Before describing the operation of each phase in detail, we explain a new control packet (RFC: request for cooperation). Fig. 3 presents the format of an RFC packet. The address field in an RFC packet is specified as a broadcast address, rather than a specific node address, to contact every relay node. Relay nodes participate in a cooperative communication after receiving the RFC packet. An RFC packet has an additional SN field, which is the sequence number of the RFC packet. The initial value of the SN field is zero; it is increased by one whenever an RFC packet is transmitted. When the cooperative communication is complete, its value is reset to zero. Relay node operations are different according to the value of the SN field. When the value is zero, relay nodes sequentially execute the awareness, group selection, and data-forwarding phases. When it is greater than or equal to one, they execute only the data-forwarding phase.

Bytes:	2	2	6	1	4
	Frame Control	Duration/ ID	Address	SN	CRC

Fig. 3. Format of RFC packet

When the destination node receives a data packet with error, it sets the SN field value to zero and transmits an RFC packet to the nodes in the network to initiate cooperative communication. Every node knows the start of the cooperative communication from the RFC packet.

After receiving the RFC packet from the destination node, nodes begin the awareness phase. Each node determines whether it can be a relay node. If a node meets the following two criteria, it becomes a relay node; otherwise, it does not become a relay node (i.e., it is a non-relay node): i) a node receives both the original data packet and the RFC packet successfully, and ii) the data rate of a node is higher than that of the source node. A node knows the data rate of the source node from the header of the received data packet.

All the relay nodes transmit their busy signals after SIFS time. If the destination node receives the busy signals, it transmits another busy signal at the next slot time; otherwise, it does not transmit a signal. From the two busy signals, every node in the network knows the existence of relay nodes. When the non-relay nodes receive busy signals from the relay nodes and/or destination node, they set their NAVs and do not contend for the channel access to avoid collisions. When the value of the SN field in the RFC packet is zero, the non-relay nodes set their NAVs as follows:

$$NAV = (GRmax + CW_{co}) * aSlotTime \qquad (2)$$

where *GRmax* is the maximum number of groups used in the proposed RNG-MAC protocol. *CWco* is the contention window size used during cooperative communication and is set to (*CWmin* / 4 – 1), where *CWmin* is the minimum contention window size. In our case, we use a small value for *CWco* because the number of channel contending relay nodes is considerably smaller than in DCF. *aSlotTime* is the duration of a slot time.

Even though there may be no relay nodes, the proposed RNG-MAC protocol functions properly. Fig. 4 presents an example where there are no relay nodes. A source node S sends a data packet after the backoff time expires. The destination node D receives the packet with error. Therefore, it sets the SN field to zero and sends an RFC packet. However, there are no nodes that meet the two criteria above. Hence, the nodes do not send busy signals after the SIFS time; the destination node also does not send a busy signal. Nodes do not set the NAV because busy signals are not sent and hence, not received. Consequently, cooperative communication fails. The source node attempts to send the data packet again through direct communication. Even though there are no relay nodes between the source node and the destination node, the proposed protocol does not waste channel time.

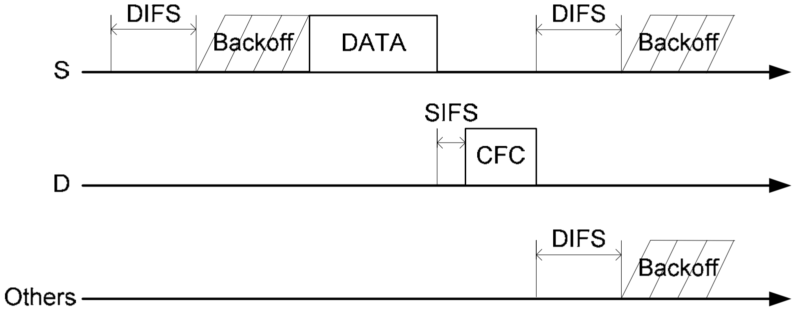

Fig. 4. Example of no relay nodes

After receiving a busy signal from a destination node, the relay nodes begin the group selection phase. In the C-ARQ protocol, all the relay nodes contend for channel access to forward the original data packet. Therefore, high collision probability can occur in a dense network. In the proposed protocol, the relay nodes are divided into several groups based on their data rates. Then, only the relay nodes in the highest group are selected and execute the data-forwarding phase. This limits the number of channel contending relay nodes and reduces the collision probability.

A relay node determines its own group based on the data rate between itself and the destination node in a distributed manner. Fig. 5 presents the groups based on the data rates between the relay nodes and the destination node. For example, the data rates for nodes “1” and “3” are 36 Mbps and 24 Mbps, respectively. Therefore, they belong to Group 2 and Group 3.

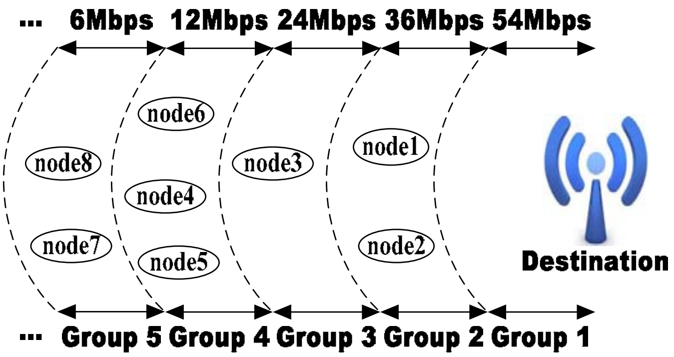

Fig. 5. Groups of relay nodes

After determining the group number, a relay node in Group n transmits a busy signal at the nth time slot to identify what group is the highest among the relay node groups. If a node senses a busy signal from other relay nodes before its own busy signal transmission time slot, it does not transmit a busy signal. Therefore, the relay nodes in the highest group among the relay nodes are selected. A relay node that senses a busy signal and is not selected, sets its own NAV as per the following to not interrupt the operation of the selected relay nodes:

$$NAV = CW_{co} * aSlotTime \tag{3}$$

Only the selected relay nodes execute the data-forwarding phase. There may be several selected relay nodes and they can collide with each other. To solve the collisions, we use a backoff mechanism. A selected relay node uniformly chooses its backoff time within *CWco*. If the medium is determined to be idle for the duration of the backoff time, the node forwards the original data packet to the destination node. If the destination node receives the data packet without error, it returns an ACK packet; otherwise, it increases the value of the SN field by one and sends an RFC packet. Only the collided relay nodes re-execute the data-forwarding phase after receiving the RFC packet. Other nodes including not collided, not selected, and non-relay nodes set their NAV using (4) and terminate their operation.

$$NAV = SIFS + CW_{co} * aSlotTime \qquad (4)$$

The data-forwarding phase is repeated until the data packet is correctly delivered to the destination node.

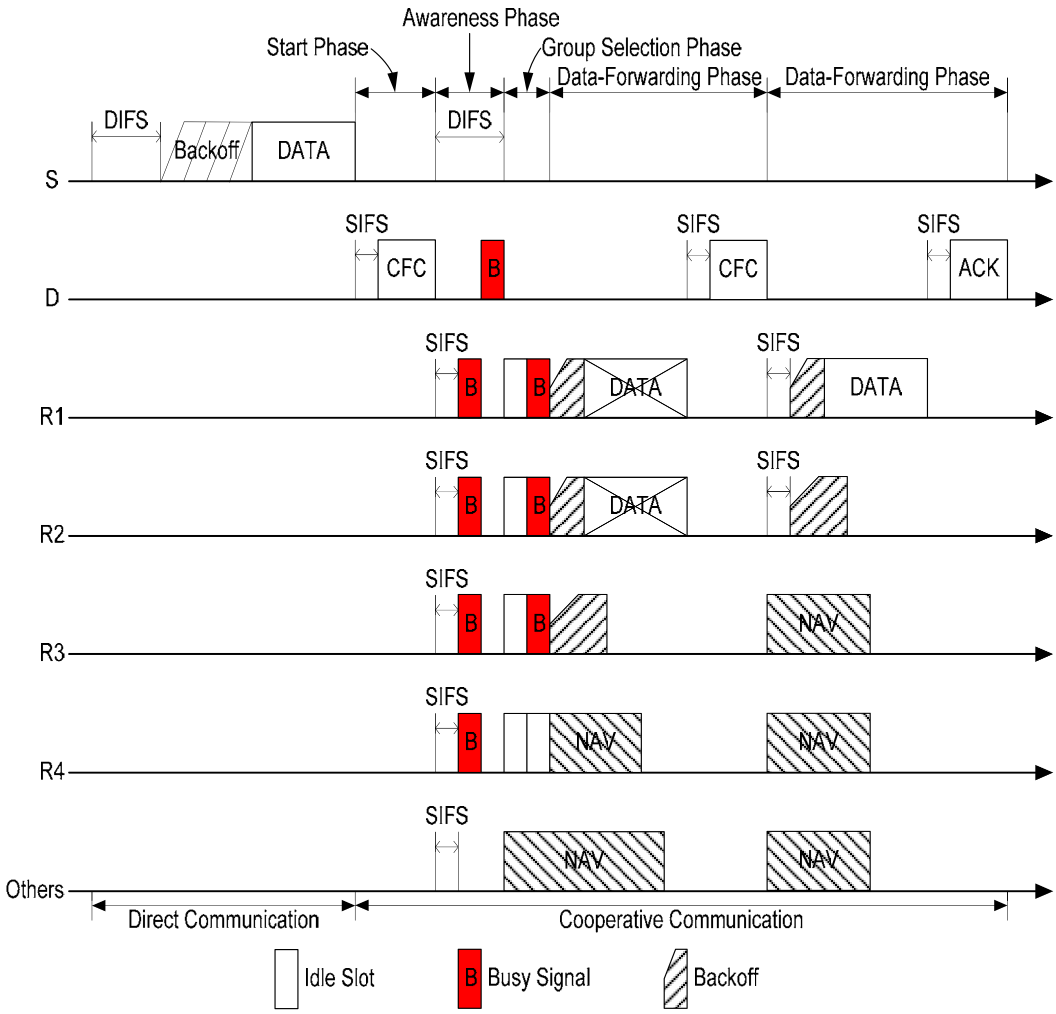

Fig. 6. Operation of the proposed RNG-MAC protocol

Fig. 6 presents an example of the operation of the proposed RNG-MAC protocol. In the figure, there are several nodes: source node (S), destination node (D), relay nodes (R1, R2, R3, and R4), and others. Node S transmits a data packet to node D through a direct communication when its backoff timer expires. Node D receives the data packet with error. It sends an RFC packet including an SN field of zero. Every node receives the data packet and RFC packet without error and knows the start of the cooperative communication. R1, R2, R3, and R4 meet the two criteria above and become relay nodes. However, the others do not meet the criteria and do not become relay nodes. All the relay nodes transmit their busy signals after SIFS time. Node D also transmits another busy signal at the next slot time. Every node knows the existence of the relay nodes. Others set their NAVs using (2) after receiving the busy signals from the relay nodes and/or node D. In the group selection phase, R1, R2, R3, and R4 determine their groups based on data rates. We assume that the data rates for R1, R2, and R3 are 36 Mbps; R4 is 24 Mbps. Their groups are “2”, “2”, “2”, and “3”, respectively. To select the highest group among the relay nodes, R1, R2, and R3 send busy signals at the second time slot; R4 senses the busy signals and does not send its busy signal. R1, R2, and R3 are selected as the highest group. R4 sets its NAV using (3). To forward the original data packet, R1, R2, and R3 execute the backoff mechanism. R1 and R2 forward the data packet after their backoff times expire. However, the data packets collide. Therefore, node D increases the SN field value by one and resends an RFC packet. Only collided nodes R1 and R2 repeat the data-forwarding phase. The other nodes (R3, R4, and others) set their NAVs using (4) because they receive the RFC packet with an SN field of one. Then, R1 forwards the original data packet to node D after backoff, and node D sends an ACK packet because it correctly receives the data packet. Finally, the cooperative communication for node S is complete. Although we do not explain the NAV update after receiving the data packets in Fig. 6, the proposed protocol updates the NAV, as in DCF.

We summarize the method to set the NAV in TABLE I based on the value of the SN field. In the table, the example field means the nodes in Fig. 6.

TABLE I: NAV value according the SN field

Node		SN = 0	SN >= 1	Example
Selected Relay	Collided	X	X	R1 & R2
	Not Collided	X	$SIFS + CW_{co} * aSlotTime$	R3
Not Selected Relay		$CW_{co} * aSlotTime$	$SIFS + CW_{co} * aSlotTime$	R4
Non Relay		$(GRmax + CW_{co}) * aSlotTime$	$SIFS + CW_{co} * aSlotTime$	Others

IV. SIMULATION RESULTS

In this section, we discuss the simulation results of the proposed RNG-MAC protocol. To study the performance of the RNG-MAC protocol, we actually implemented the protocol. We compared the results to the results of the C-ARQ protocol. The system parameters used in the simulation are listed in TABLE II. We simulated an IEEE 802.11a network with a maximum data rate of 54 Mbps. Nodes were uniformly distributed in a square area of 250 m × 250 m. A destination node was placed at the centre of the square. A fixed number of nodes were randomly distributed over the network. The data rates and groups of the nodes in the simulation network depended on the distance between the nodes and the destination node (see TABLE III). In the simulation, we considered only uplink traffic.

A constant data packet size of 1,500 bytes was used. We assume a data packet error rate of 0.2. Simulations executed for 100 seconds and all simulation results were averaged over 10 simulations.

TABLE II: Simulation parameters

Parameter	Value
Maximum Data Rate	54 Mbps
Slot Time	9 us
SIFS	16 us
Propagation Delay	1 us
MAC Header	25 Bytes
CRC	4 Bytes
PHY PLCP Preamble Length	16 us
PHY PLCP Header Length	5 Bytes
Packet Size	1500 Bytes
CWmin	31

TABLE III: Data rates and groups according to the distance

Distance (m)	Group	Data Rate (Mbps)
< 31	1	54
31 ~ 60	2	36
61 ~ 74	3	24
75 ~ 95	4	12
96 ~ 121	5	6
122 ~ 150	6	2
> 150	7	1

The main performance metrics of interest are throughput, collision probability, and average delay. The average delay is the time between a data packet arrival at the queue of a source node and the successful data packet transmission to the destination node.

Fig. 7 indicates the collision probability according to the number of nodes. From this figure, we can observe that the collision probability increases as the number of nodes becomes larger. However, the graph is not linear and fluctuated because nodes are randomly distributed in the simulation network. The collision probability was generally high. As mentioned, we assumed in the simulation that the data packet error rate was 0.2. A node did not distinguish between errors and collisions. Therefore, errors were also considered as collisions. The proposed RNG-MAC protocol was lower than the C-ARQ protocol in all cases because in the proposed protocol, the relay nodes were grouped and some of them were selected from the highest group. Only the selected relay nodes contended for the channel to forward the original data packets to the destination node, resulting in lower collision probability. In the C-ARQ protocol, all the relay nodes attempted to send the original data packets and caused collisions with each other.

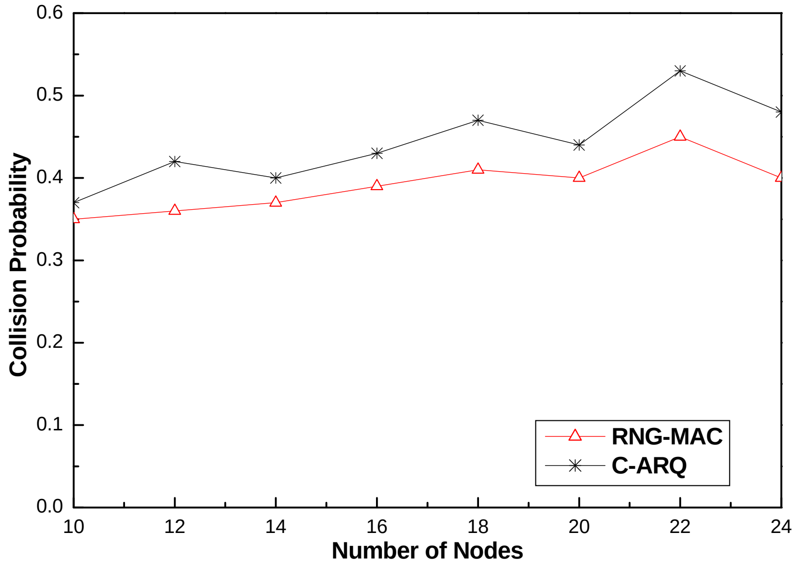

Fig. 7. Collision probability according to the number of nodes

Fig. 8 depicts the throughput according to the number of nodes. The C-ARQ protocol indicates a reduced throughput because collision probability increases as the number of nodes becomes larger. However, the RNG-MAC protocol has a high throughput regardless of the number of nodes in the network. The reason is that the RNG-MAC protocol always selects the relay nodes with the best data rate and limits the number of relay nodes contending for channel access.

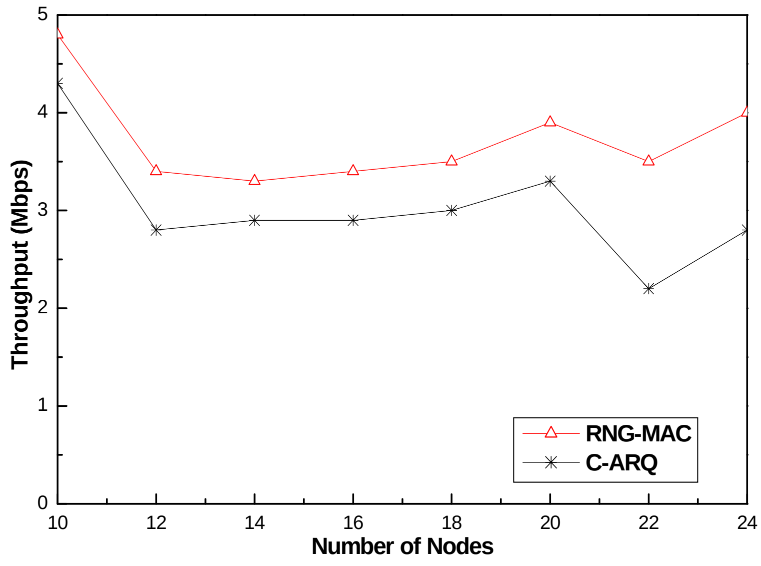

Fig. 8. Throughput according to the number of nodes

Fig. 9 presents the results for average delay according to the number of nodes. The average delay of both protocols is not low owing to a high collision rate. However, the RNG-MAC protocol has a lower delay compared to the C-ARQ protocol.

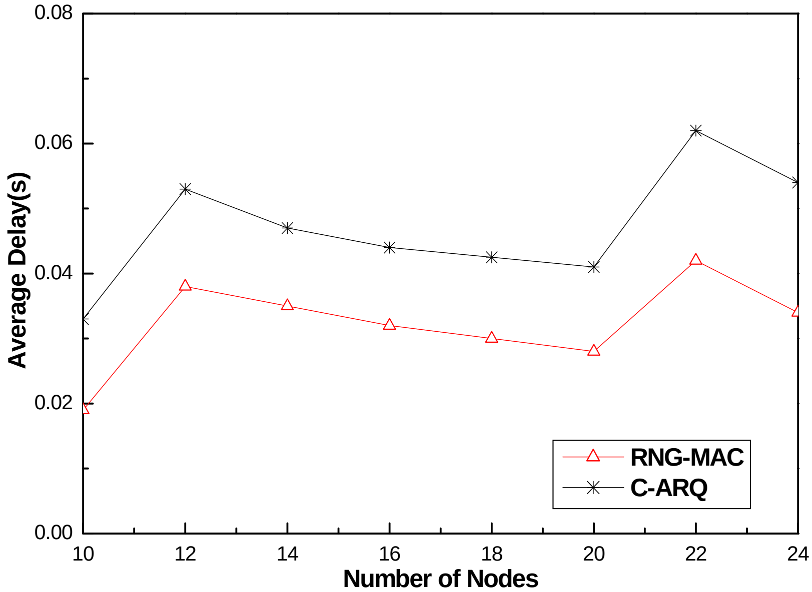

Fig. 9. Average delay according to the number of nodes

V. CONCLUSION

IEEE 802.11a/b/g standards support multiple data rates. Cooperative communication for wireless networks has attracted considerable interest. In cooperative communication, a number of relay nodes support a source node in forwarding data packets to a destination node. In the C-ARQ protocol, all the relay nodes attempt to forward the original data packet to the destination node. This approach can cause collisions with each other. Cooperative communication can be interrupted by other nodes. To resolve these problems, we proposed the RNG-MAC protocol. In the proposed protocol, relay nodes are divided into several groups based on their data rates. Then, only the relay nodes in the highest group are selected to acquire channel access. Collisions among the selected relay nodes are resolved based on a backoff mechanism. The proposed protocol ensures that cooperative communication is not interrupted by other nodes by implementing busy signals and NAV. Therefore, the proposed protocol can reduce the collision probability and increase the network performance. Simulation results confirmed that the proposed protocol significantly outperformed the C-ARQ protocol in terms of throughput, collision probability, and delay.

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