A Cooperative MAC Protocol Based on 802.11 in Wireless Ad hoc Networks

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***Abstract*—Cooperative communications among nodes is an efficient method to decrease signal fading and interference in MAC layer of wireless Ad hoc networks. However, the previous cooperative MAC protocols are designed for IEEE 802.11b, but not for later standard IEEE 802.11g or 802.11n. To increase performance, improve reliability and reduce energy consumption in communications, we propose a cooperative MAC protocol for IEEE 802.11g and being extended to 802.11n. By partitioning the relays with similar transmission rates into same groups, we can reduce efficiently the time for selecting better relays to help data transmission. Furthermore, we propose a novel retransmission scheme to reduce the retransmission time, while once data transmission is fail, only the relays which have received the data frame will help for retransmission instead of repeating all retransmission cycle. Simulation results show that our proposed protocol outperforms previous work by increasing the throughput and reducing the average delay time in transmission.**

Keywords- Cooperative communications*; *MAC protocol*; *IEEE 802.11*; *wireless Ad hoc networks

I. INTRODUCTION

In recent years, more and more internet accesses through wireless Ad hoc networks is provided and used in many places, such as convenience stores, hospitals, and airports. However, signal fading and interference are two main problems leading to decreasing network performance in applications. In order to deal with these problems, cooperative transmission among nodes based on IEEE 802.11 standard [1] is proposed as a critical important solution. By an efficient cooperative communication Medium Access Control (MAC) protocol, we cannot only improve network performance and reliability, but also reduce power consumption of nodes.

In the existing cooperative MAC protocols, there are two necessary phases. In the first phase, the source transmit data frame, it can be overheard simultaneously by both the destination and the relay nodes; in the second phase, relay nodes whose Signal-to-Noise Ratio (SNR) is higher than direct transmission from source to destination would help to forward the data frame to destination instead of direct transmission. In another word, source node can use more reliable and faster link from relays to transmit data to destination, it can reduce effectively the delay time of transmission. In general, the more the helper number is, the more reliable the transmission is. However, when we increase the number of relay nodes, the communication interference will be enlarged and the control overhead will increase. Moreover, the selection time for relays will increase and transmission efficiency will decrease. So it is essential that we have to utilize limited relays and their bandwidth resources to achieve the transmission from source to destination efficiently.

In this paper, we proposed an efficient cooperative MAC protocol based on IEEE 802.11g which can be extended to the later version standard, IEEE 802.11n based on their similar architecture, transmission mechanism, and frame control format. In our approach, after the source sends a Ready To Send (RTS) message to destination to request for transmission, it only needs to wait less time slots than previous work to find if there are relays which can help to transmit packets based on the replying message Clear-To-Send (CTS). If there are available relays, each relay will reply a Relay-Ready-To-Send (RRTS) frame to tell source it can help to forward packets. Then the source will choose the relays which have the highest data rates of source-to-relay and relay-to-source to help for transmission. Moreover, multiple relays with same highest transmission rate can transmit same data at the same time slots, which can increase the signal strength and improve the transmission reliability. If the current transmission is fail, source will not receive Acknowledgement (ACK) message from destination, relays will send a Relay-Acknowledgement (RACK) frame to source and help to retransmit data immediately with faster transmission rate than direct transmission. By relay selection scheme and retransmission scheme, we can improve the transmission efficiency and reduce the cooperative communication overhead. In simulation result, it is shown that our protocol increases throughput 10% in average than CoopMAC protocol [2] when the frame loss rate is less than or equal to 30%. When the frame loss rate is greater than 30%, our protocol increases throughput 20% in average than CoopMAC protocol.

The rest of this paper is organized as follows. Section II describes related work of cooperative MAC protocols. We introduce detailed approach of our cooperative MAC protocol

This work was supported by the NSC of Republic of China under grants NSC 101-2221-E-007-023.

in Section III. The simulation results and performance evaluation are shown in Section IV, and Section V concludes this paper.

II. Related Work

In IEEE 802.11 standards, there are only mechanisms designed for direct communications, but not for cooperative communications, which can improve network performance and reliability. Actually, cooperative MAC protocols can increase the data transmission efficiency and reduce network transmission delay by selecting high-data-rate relays to help for transmission between source and destination.

In [3], the authors built and maintained a relay information table. When a source try to send data, the source begin to search the table to find if there are relays whose transmission rate is higher than direct transmission and choose one of fastest relays to help for transmission. In [4], the authors used the response frames of relays to detect their transmission rates and select the best one to help for transmission. Approaches in [5, 6] were proposed to select relays and control their transmission energy to achieve energy efficient transmission. These schemes observe previous transmission information in order to decrease the total energy consumption and prolong network lifetime. In [7], the authors considered two kinds of cooperative MAC protocols and designed a link-utility equation calculated by both transmission time and energy cost. Then source can select relays based on the link-utility to improve the performance of throughput under acceptable energy consumption. In order to offer efficient interaction between the physical layer and higher protocol layers, MAC protocol design based on distributed cooperative communication is necessary.

The papers above made effort to improve the actual transmission rate or reduce energy consumption, but they did not consider the signal strength. In fact, the larger signal strength is, the smaller the data loss rate is, so that it is an efficient method to improve the transmission reliability and decrease the number of retransmission by enlarging the signal strength. The cooperative MAC protocols were proposed which use signal combination and amplification technology to enlarge the signal strength. In [8], the authors proposed a differential Amplify-and-Forward (AF) transmission scheme. In the AF scheme, signal transmission can be separated into two phases. In the first phase, the source sends out the symbol to relay; in the second phase, the relay amplifies the received signal by the technology of Differential M-ary Phase-Shift Keying (DMPSK) and forwards it to destination. The transmission scheme can combine efficiently the signals to improve the SNR and decrease bit-error-rate (BER). In [9], the authors implemented signal amplification and improvement of communication by combining the data frame transmitted by source and relays.

However, these papers did not propose efficient retransmission schemes when transmissions fail. When the destination does not receive packets successfully, sender has to repeat all the transmission cycle, which will cost more energy and increase the delay time of communication.

III. Protocol Design

We design a cooperative MAC protocol based on IEEE 802.11g, which can support ten different data rates, including 1, 2, 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. Our protocol can be modified to use in IEEE 802.11n. In the following, we will propose a cooperative scheme after the system model is built. Moreover, we present the relay selection scheme of the cooperative MAC protocol. In order to solve the problem of transmission failure, we propose a packet retransmission scheme in the last part of this section.

A. System model

As shown in Fig. 1, S, D and R_i (i = 1, 2, …, n) denote the source, the destination and the ith relay, respectively, and R_{SD}, R_{SRi}, and R_{RiD} denote the data rates between S and D, S and R_i, R_i and D, respectively. Source S can transmit data directly to destination D or select faster relays to help for data transmission. The available data rate depends on the average received SNR during certain communication periods. The data rate of control frames (RTS, CTS, ACK) is set to 1 Mbps as basic rate so that all of nodes can receive them.

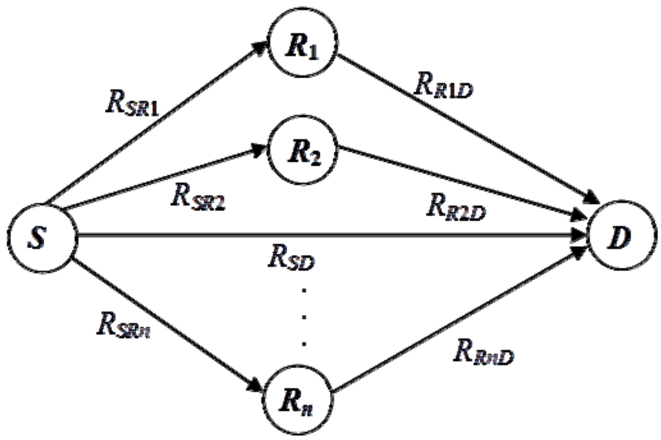


Figure 1 System model of cooperative MAC protocol based on IEEE 802.11g

B. Cooperative MAC scheme

When source node finds channel is idle and it can transmit data frame to destination node, it will send an RTS frame to destination and wait for a CTS frame from destination. If a common node except source and destination can overhear both RTS and CTS frames, it means that this node can communicate with both source and destination, in another word, this common node can serve as a relay candidate. Each relay candidate will calculate the data rates from itself to the source and destination according to the SNR information in received control frames or data frames. Moreover, these relay candidates will reply RRTS frames to tell source that they can help for transmission based on the collected data rates of R_{SD}, R_{SR}, and R_{RD}. In fact, the fastest relay candidates will reply the RRTS frame earliest to the source node after receiving CTS. We intend to select these fastest relay candidates as relay nodes to help transmitting data frame. Then, source node will transmit data frame to relay nodes, and the relay nodes with the highest data rate will forward the data frame to destination. If destination receives data frame successfully from relay nodes, it will reply ACK frame to source.

The process is shown in Fig. 2. The DIFS and SIFS denote DCF (Distributed Coordinated Function) InterFrame Space and Short InterFrame Space, respectively.

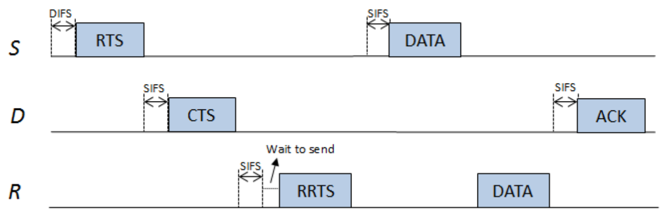


Figure 2 Source sends data to destination through relay

If source cannot receive any RRTS frame within a specific time period which is denoted by *Wait-RRTS*, the source will transmit data frame to destination directly. After the transmission is finished, the source will set another timer to wait for ACK. If destination receives data frames successfully and replies an ACK frame to source, it means the transmission is completed. However, if the source cannot receive ACK frame from destination within the specific time period, it will set up a *Wait-RACK* timer to wait for relays' help. If no RACK frame is received after *Wait-RACK* timer is expired, source will retransmit data frame to destination also by direct retransmission. If the source receives RACK frames, it will ask the relay nodes to help to retransmit data frame to destination. Finally, the communication will be completed if the source receives an ACK message successfully from destination. Otherwise, the source will perform a retransmission procedure, following IEEE 802.11 standard.

C. *Relay selection scheme*

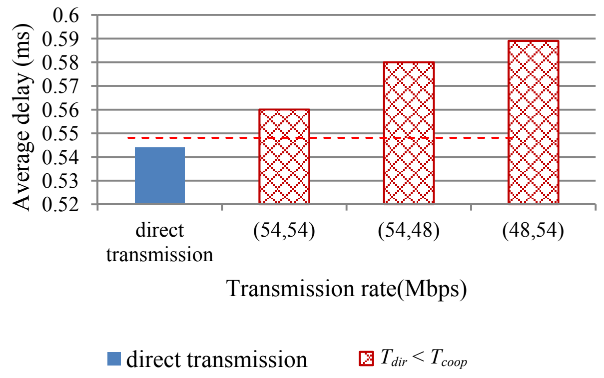
In CoopMAC, the summation of the transmission time from source to relay node and it from relay node to destination must be less than the direct transmission time from source to destination. So, relay node R_i which can be selected as a helper for transmission must satisfy the following constraint:

$$\frac{1}{R_{SRi}} + \frac{1}{R_{RiD}} < \frac{1}{R_{SD}} \qquad (1)$$

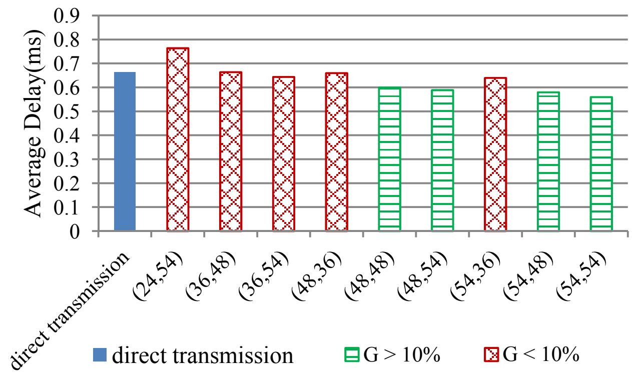
These data rates can be obtained through message exchanges among source, relay nodes, and destination. To select efficiently the proper relays, we will use Network Simulator version 2 (NS-2) [10] to evaluate the performance of direct transmissions and cooperative transmissions in different data rates. Each relay will use equation (1) to estimate whether it can help to transmit data frame.

According to the evaluation, the average delay times of direct communications and cooperative communications under different transmission rates of R_{SD}, R_{SR}, and R_{RD} will be partitioned into different groups. We use data-rate-pairs to denote the transmission rates from source to relay and relay to destination, for example, (54, 48) denotes that the transmission rate from source to relay is 54 Mbps, and the transmission rate from relay to destination is 48 Mbps. We use T_{dir} to denote the direct communication time from source to destination and use T_{coop} to denote cooperative communication time, summated by the time from source to relay and the time from relay to destination. The gain of cooperative communication over direct communication is denoted as $G = (T_{dir} - T_{coop}) / T_{dir}$. In order to reduce the relay selection time, the relays whose G are less than 10% will not be considered as relay candidates because of their less contribution of help for transmission. Furthermore, the relays which have the similar average delay times will be partitioned into same groups.

In Fig. 3(a), if direct transmission rate is 24 Mbps, no relay can help for transmission faster than direct communications because source has to transmit data frame to destination by two-hop transmission under indirect communication method. It will wait for additional control overheads from relays, such as RRTS, which can increase the delay time and decrease the performance of cooperative communications. We can obtain similar evaluation results when the direct transmission rates are 36, 48, and 54 Mbps, besides 24 Mbps.



(a) R_{SD} = 24 Mbps



(b) R_{SD} = 18 Mbps

Figure 3 Average delay time under different transmission rates

As shown in Fig. 3(b), when the direct transmission rate from source to destination is 18 Mbps, the average delay of the direct transmission is less than or equal approximately to the cooperative transmission with relay if the data-rate-pairs are (24, 54), (36, 48), (36, 54), (48, 36), and (54, 36). In another word, we only need to consider the case whose data-rate-pairs are (48, 48), (48, 54), (54, 48), and (54, 54), where $R_{SR} \geqq 48$ Mbps and $R_{RD} \geqq 48$ Mbps, which have the shorter delay time than the direct communication. Each node belongs to the four data-rate-pairs can serve as a relay candidate. To speed up the relay selection procedure, we will put the four data-rate-pairs into same group because of their approximate average delay. According to this method of group partition, we can build Table I (while $R_{SD} \leqq$ 18 Mbps). For example, if the direct transmission rate R_{SD} is 12 Mbps, the relay candidates can be partitioned into three groups, as shown at the third row in Table I. In order to reduce the number of groups, we combine the cases of R_{SD} = 1 Mbps and R_{SD} = 2 Mbps and put the combined cases into groups by average delay times as shown in the last row of Table I. Moreover, according our evaluation, the relays with R_{RD} < 6 Mbps will not be used to help for data transmission, so that they are not listed in Table I.

Based on our relay partition scheme, the relays belong to the same group may have different transmission rates. In actual cooperative communications, the relays will use the lowest transmission rate of the group to send their control or data frames simultaneously. For example, if R_{SD} = 18 Mbps, the relays with $R_{SR} \geqq$ 48 Mbps and $R_{RD} \geqq$ 48 Mbps are partitioned into Group 1. In transmission, we will let all relays transmit their RRTS frames to source node with the lowest speed of R_{SR} = 48 Mbps. Thus, all of the relays in Group 1 will also use the same transmission rate to transmit data frames simultaneously. On the destination, these frames will be combined and their signals will be amplified by the technology of DMPSK mentioned in Section II, which can improve the SNR and reliability of data transmission. We can efficiently combine signals and encode them from all branches, in which only the long-term average of the received signals is required as sufficient statistics to calculate and decode the combining information without acquiring the Channel State Information (CSI) [8].

In actual transmission, a source can quickly determine whether there exist relays which can help to forward data frames within *n* time slots (*n* is equal to the number of groups) according to Table I. If a relay finds its cooperative transmission rate belongs to Group *i*, it will send an RRTS frame, which is designed based on the frame control format of IEEE 802.11, to the source node in the *i*th time slot if previous *i*-1 time slots are idle. Source will transmit data frames to relays with a proper R_{SR} when it receives the RRTS.

For example, if R_{SD} = 12 Mbps, there are three groups of relays which can help for cooperative transmission as shown in Table I. we can observe whether there are relays which can help for data transmission within three time slots. At the first time slot, the source will wait for the RRTS sent by the relays which satisfy $R_{SR} \geqq$ 48 Mbps and $R_{RD} \geqq$ 48 Mbps in Group 1 because of their fastest transmission rate. If there are two relays whose transmission rates are (48, 48) and (54, 48), the source will transmit data frame to both relays on the lower transmission rate R_{SR} = 48 Mbps. After the two relays receive the data frame, they will forward the frame to destination with the lower transmission rate R_{RD} = 48 Mbps simultaneously. If there are no relay candidates in Group 1, the source will wait for the RRTS from the relays in Group 2, which satisfy (R_{SR} = 36 Mbps and $R_{RD} \geqq$ 36 Mbps) or ($R_{SR} \geqq$ 36 Mbps and R_{RD} = 36 Mbps) at the second time slot, and so on.

If a source node cannot receive any RRTS within a time period, *Wait-RRTS*, it means that there is no relay can help for cooperative communications, so that the source must transmit the data frames directly. The length of *Wait-RRTS* is the length of a time slot multiplied by the number of groups on each R_{SD}. If there are *n* groups on a particular R_{SD}, the *Wait-RRTS* is equal to the length of *n* time slots.

TABLE I. GROUP PARTITION BASED ON DIFFERENT R_{SD} (Unit: Mbps)

Group / R_{SD}	1	2	3	4	5
18 Mbps	$R_{SR}\geqq 48$ and $R_{RD}\geqq 48$				
12 Mbps	$R_{SR}\geqq 48$ and $R_{RD}\geqq 48$	$R_{SR}=36$ and $R_{RD}\geqq 36$ or $R_{SR}\geqq 36$ and $R_{RD}=36$	$R_{SR}=24$ and $R_{RD}\geqq 48$ or $R_{SR}\geqq 48$ and $R_{RD}=24$		
9 Mbps	$R_{SR}\geqq 48$ and $R_{RD}\geqq 48$	$R_{SR}=36$ and $R_{RD}\geqq 36$ or $R_{SR}\geqq 36$ and $R_{RD}=36$	$R_{SR}=24$ and $R_{RD}\geqq 24$ or $R_{SR}\geqq 24$ and $R_{RD}=24$	$R_{SR}=18$ and $R_{RD}\geqq 36$ or $R_{SR}\geqq 36$ and $R_{RD}=18$	
6 Mbps	$R_{SR}\geqq 48$ and $R_{RD}\geqq 48$	$R_{SR}=36$ and $R_{RD}\geqq 36$ or $R_{SR}\geqq 36$ and $R_{RD}=36$	$R_{SR}=24$ and $R_{RD}\geqq 24$ or $R_{SR}\geqq 24$ and $R_{RD}=24$	$R_{SR}=12$ and $R_{RD}\geqq 24$ or $R_{SR}\geqq 24$ and $R_{RD}=12$	
1 or 2 Mbps	$R_{SR}=36$ and $R_{RD}\geqq 36$ or $R_{SR}\geqq 36$ and $R_{RD}=36$	$R_{SR}=24$ and $R_{RD}\geqq 24$ or $R_{SR}\geqq 24$ and $R_{RD}=24$	$R_{SR}=18$ and $R_{RD}\geqq 18$ or $R_{SR}\geqq 18$ and $R_{RD}=18$	$R_{SR}=9$ and $R_{RD}\geqq 9$ or $R_{SR}\geqq 9$ and $R_{RD}=9$	$R_{SR}=6$ and $R_{RD}\geqq 6$ or $R_{SR}\geqq 6$ and $R_{RD}=6$

D. Retransmission scheme

There are three kinds of data transmission failures including data transmission failure from source, data forwarding failure from relays, and ACK replying failure from destination. Actually, all the three failures can lead to no ACK received by source node, so we propose a retransmission scheme to cover for the failures. We know that if $R_{SD} \geqq$ 48 Mbps, no cooperative communication can help to reduce the end-to-end delay. Therefore, the source will retransmit data to destination directly in this case.

If R_{SD} < 48 Mbps, source will set a timer *Wait-RACK* and wait for the RRTS from relays which can help to retransmit data frame after exchanging RTS and CTS with destination. Similar to the relay selection scheme, the relays with faster data transmission rate will reply RACK earlier. Each relay which has received the source data frame and satisfies $R_{RD} \geqq \alpha R_{SD}$ will reply a RACK frame to source. Based on the experiments results, we choose an higher efficient coefficient value and set α = 1.5. To reduce the time of waiting RACK, the relays with

$R_{RD} \leqq 6$ Mbps will not be used to help for data retransmission. For example, when $R_{SD} = 2$ Mbps, the appropriate relays must satisfy $R_{RD} \geqq 3$ Mbps and $R_{RD} > 6$ Mbps, which are in 9, 12, 18, 24, 36, 48, and 54 Mbps. As a result, the maximum waiting time of *Wait-RACK* is equal to 7 time slots when $R_{SD} \leqq 2$ Mbps. If the source receives the RACK frame before its *Wait-RACK* timer is expired, it means that there are relays which can help to retransmit data frame and it will be faster than direct retransmission. The source node will ask the relays to retransmit the data frame which have been received by the relays. Multiple relay candidates with the same data rate will response RACKs at the same time, so that the data retransmission can be done by the help of these relays based on signal combination for more reliability. If no RACK is received after *Wait-RACK* timer is expired, the source will retransmit data directly.

IV. Performance Evaluation

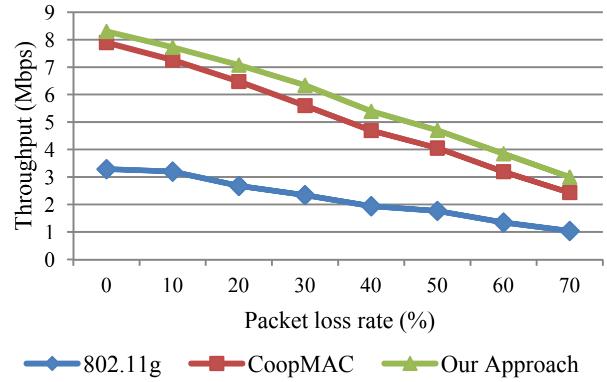
The performance of our protocol is evaluated by the simulations on NS-2 and we will compare our protocol with IEEE 802.11g and CoopMAC protocol by the throughput and the end-to-end delay. We use TwoRayGround model [11] as radio propagation model and Ad hoc On-Demand Distance Vector Routing (AODV) [12] as network layer routing protocol. The set of main simulation parameters follows the default values specified in IEEE 802.11g as shown in Table II.

TABLE II. PARAMETERS USED IN SIMULATIONS

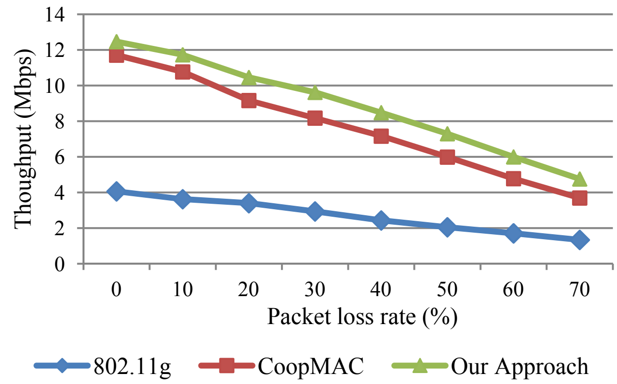
Parameter	Value	Parameter	Value
PHY header	192 bits	DIFS	28 μsec
MAC header	272 bits	Slot time	9 μsec
RTS	160 bits	CW_{min}	31 slots
CTS, ACK, RRTS, RACK	112 bits	CW_{max}	1023 slots
SIFS	10 μsec		

In our simulations, mobile nodes are placed randomly in a 250m × 250m area. The transmission range of node is 100m and the moving speed of node is from 0m/s to 10m/s. Two scenarios are designed based on different data frame sizes, 512 bytes and 1024 bytes. We will change the packet loss rate to simulate different interferences in environment.

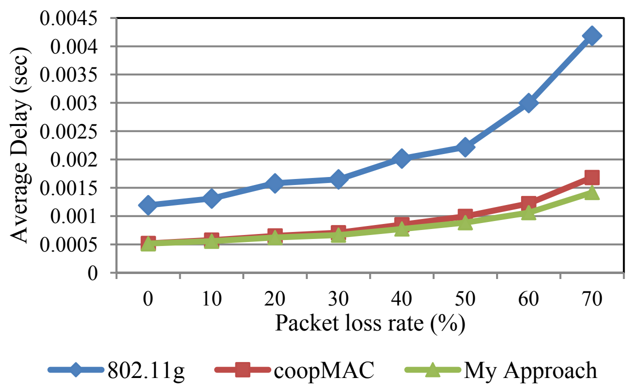
Firstly, we compare our protocol in the throughput and average delay with IEEE 802.11g and CoopMAC as shown in Fig. 4. In Fig. 4(a) and 4(b), because we partition the relays into different groups to reduce the relay selection time, our protocol's throughput outperforms IEEE802.11g's remarkably, outperforms CoopMAC's by 12% and 15% in average when the packet sizes are equal to 512 bytes and 1024 bytes, respectively. We can also notice that the larger the packet size is, the more the throughput improvement is, because the ratio of control frame overhead (such as PHY and MAC overhead) is different in different packet sizes: the larger the packet size is, the less the ratio of control frame overhead is. Moreover, the average throughput of our protocol is 10% better than CoopMAC when the packet loss rate is less than 30%, and it will increase to 20% better than CoopMAC when the packet loss rate is greater than 30%, due to our more efficient retransmission scheme. We can use faster relays to help source node to retransmit data frame instead of low data rate direct transmission, which can improve the average throughput and reduce the delay time of retransmission. In addition, the average delay of out protocol is better than IEEE 802.11g, and slightly better than CoopMAC as shown in Fig. 4(c).



(a) Throughputs of three protocols (packet size = 512)



(b) Throughputs of three protocols (packet size = 1024)

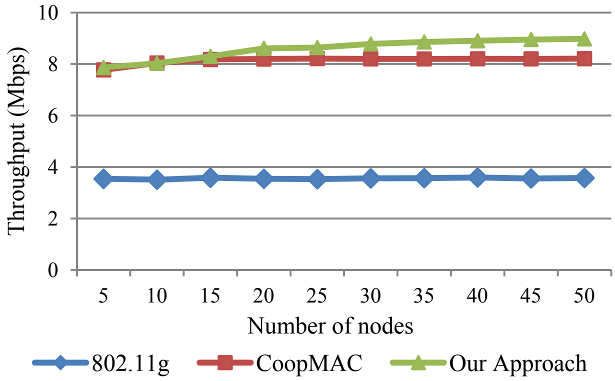


(c) Average delay times of three protocols

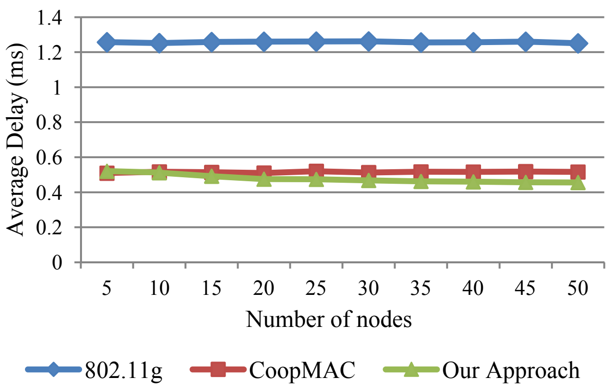
Figure 4 Throughputs and average delay times under different packet loss rates

In Fig. 5, we change the number of nodes to observe the throughputs of IEEE 802.11, CoopMAC and our protocol. When the number of nodes is less than 20, the throughput and delay of our protocol are approximately equal to that of

CoopMAC, because the probability of finding appropriate relays will be low when number of nodes is small. Moreover, the relays belong to same group will use the lowest transmission rate to transmit data frames; it will also decrease the throughput.



(a) Throughputs of three protocols



(b) Average delay times of three protocols

Figure 5 Throughputs and average delay times under different numbers of nodes

When the number of nodes is greater than 20, the throughput of our protocol increases and the delay time of our protocol decrease along with the increasing of nodes because the source node can find relays to help transmission with higher probability. The throughput and the average delay of our protocol is about 10% higher and 10% lower than CoopMAC protocol, respectively. When the number of nodes is greater than or equal to 45, the throughput of our protocol will be stable at 9 Mbps because we can find enough relays with fast transmission rate to help for cooperative communications.

V. CONCLUSION

In order to deal with the problems of signal fading and interference in wireless Ad hoc networks, cooperative communications is considered as an important solution. In this paper, we propose a cooperative MAC protocol based on IEEE 802.11. In our protocol, the relays are partitioned into different groups according to their communication performance under different transmission rates from source to destination, and we allow the relays which are in same group to help source to transmit data cooperatively. Furthermore, we propose a retransmission scheme to reduce the time cost and improve the performance of data frame retransmission. By simulation, we evaluate the performance of our protocol, and the results show that our protocol outperforms the previous works by throughput and average delay time.

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