CRP-CMAC: A Priority-Differentiated Cooperative MAC Protocol with Contention Resolution for Multihop Wireless Networks

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Abstract

To improve the cooperative efficiency of node cooperation and multiple access performance for multihop wireless networks, a priority-differentiated cooperative medium access control protocol with contention resolution (CRP-CMAC) is proposed. In the protocol, the helper selection process is divided into the priority differentiation phase and the contention resolution phase for the helpers with the same priority. A higher priority helper can choose an earlier minislot in the priority differentiation phase to send a busy tone. As a result, the protocol promptly selects all the highest priority helpers. The contention resolution phase of the same priority helpers consists of k round contention resolution procedures. The helpers that had sent the first busy tone and are now sending the longest busy tone can continue to the next round, and then the other helpers that sense the busy tone withdraw from the contention. Therefore, it can select the unique best helper from the highest priority helpers with high probability. A packet piggyback mechanism is also adopted to make the high data rate helper with packet to send transmit its data packets to its recipient without reservation. It can significantly decrease the reservation overhead and effectively improve the cooperation efficiency and channel utilization. Simulation results show that the maximum throughput of CRP-CMAC is 74%, 36.1% and 15% higher than those of the 802.11 DCF, CoopMACA and 2rcMAC protocols in a wireless local area network (WLAN) environment, and 82.6%, 37.6% and 46.3% higher in an ad hoc network environment, respectively.

Keywords: Multihop wireless networks, cooperative medium access control, helper selection, priority differentiation, contention resolution, packet piggyback

1. Introduction

In wireless networks, signal fading in the data transmission process and the signal interference among users or nodes have a significant impact on the quality of signal reception. Cooperative communication technique offers a solution to these challenges [1][2]. It uses the broadcast nature of wireless communication to engage some nodes within the communication range of the sender to be the helpers that help the sender to transmit its data packet to its recipient, thus effectively combating the signal fading, and improving the spectrum efficiency and communication reliability [3][4]. Therefore, it is being gradually used to typical wireless networks, such as next generation networks (NGNs), wireless local area networks (WLANs), wireless sensor networks (WSNs), mobile ad hoc networks (MANETs) and consumer electronic networks.

Early research work on cooperative communication technique mainly focused on the physical (PHY) layer. It is generally assumed that a recipient can receive the signals from its sender and multiple helpers either simultaneously using multiple orthogonal channels or space-time coding scheme, or sequentially using different time slots. It mainly makes a tradeoff between the cooperative diversity gain and other performance metrics, such as channel capacity, data rate, bandwidth efficiency, power efficiency, bit error rate (BER) and anti-interference capability. Recently, more and more research work has focused on applying the cooperative communication technique to the upper layers, such as the data link layer and the network layer, in order to enhance the cooperative transmission efficiency. In the data link layer, the medium access control (MAC) layer is close to the PHY layer and is used to address the channel sharing problem for multiple users or nodes [5]. How to design the MAC protocol based on node cooperation is crucial to fully exploit the cooperation gain and improve the network performance. Therefore, cooperative MAC protocols have become a hot research topic [6][7].

The objective of applying cooperative communication technique to the MAC layer to improve the multiple access performance is twofold. Firstly, it is to improve information transmission rate and throughput. Secondly, it is to enhance the link reliability and anti-interference capability [1].

The former favors node cooperation over direct transmission from a sender to its recipient. It needs to determine whether the cooperative transmission is advantageous during reservation, i.e., whether a helper can support a higher data rate from the sender to its recipient or consume shorter data packet transmission time. If so, it initiates node cooperation. Otherwise, the sender transmits its data packet to its recipient directly. The typical protocols are the cooperative MAC (CoopMAC) protocol [7], the relay-enabled distributed coordination function (rDCF) protocol [8], and so on. They exploit the higher data rate transmission from the sender to its helper and from the helper to the recipient to replace the lower data rate transmission from the sender directly to its recipient, which improves the equivalent data rate from the sender to its recipient, and decreases the transmission time of a data packet.

The latter adopts the concept of cooperative automatic repeat request (ARQ), i.e., cooperation transmission mechanism can be used only when the recipient cannot correctly receive the data packet from its sender, and then the helper retransmits the data packet to the recipient. Its typical protocols are the cooperative diversity MAC (CD-MAC) protocol [1] and the differentiated cooperative MAC (DC-MAC) protocol [9]. In the CD-MAC protocol [1], the sender and its specified best helper retransmit the data packet to the recipient

simultaneously when the direct transmission fails. It takes advantage of the enhanced signal intensity to overcome the signal fading problem and improve the anti-interference capability. In order to address the problems of the error bursts and limited signal transmission distance of high data rate nodes, the DC-MAC protocol [9] adopts cooperative ARQ mechanism and randomly chooses one of the helpers with the high enough received signal-to-noise-ratio (SNR) of its transmitted signal at the recipient to retransmit the data packet. Meanwhile, it uses the negative acknowledgment (NAK) scheme to differentiate data packet collisions and failure data packet reception caused by channel errors, and to make the channel estimation. Therefore, the proper helper is selected to retransmit the data packet only in the case of failed data packet reception, which improves the cooperation efficiency and packet transmission reliability.

Currently, more and more cooperative MAC protocols take into consideration the above two aspects, such as the space-time coding cooperative MAC (STiCMAC) protocol [10] and the two-relay-based cooperative MAC (2rcMAC) protocol [11]. In the STiCMAC protocol [10], multiple helpers adopt the random distributed space-time-coding (STC) mechanism to cooperatively transmit the data packet at the same time, and thus can combat serious signal fading. It also uses proper STC modulation and channel coding rate to increase the data transmission rate. In the 2rcMAC protocol [11], each helper estimates the highest data rates that it can support from itself to the sender and the recipient, and chooses the corresponding minislot during the relay response period to send 1 bit signal. According to the position of the 1 bit signal, the sender selects two best helpers for the first cooperative relay transmission and the second backup relay transmission. In case the first cooperative transmission fails, the backup helper relays the data packet to the recipient rather than the sender retransmits it. Therefore, it improves the throughput while guaranteeing transmission reliability.

As mentioned above, in order to obtain better cooperation gain, it is necessary to solve the problems of how to select the helper and how to cooperate. To solve these problems, a priority-differentiated cooperative MAC protocol with contention resolution (CRP-CMAC) for multihop wireless networks is proposed. According to the data rates from the helper to the sender and from the helper to the recipient, the helpers are divided into different priorities to contend the right of cooperative transmission. Then the helpers with the same priority use the proposed contention resolution scheme to select the unique best helper with the most probability. In addition, the packet piggyback mechanism is used to improve its multiple access performance. That is to say, after the high data rate helper relays the data packet of the sender, it can transmit its own data packet to its recipient without channel reservation.

The rest of the paper is organized as follows. In Section 2, the related work is introduced. The network model is given in Section 3 and the proposed protocol is described in Section 4. Simulation results are given in Section 5, followed by conclusions in Section 6.

2. Related Work

The key problem of cooperative MAC protocols is how to select the best helper from the multiple potential candidates, i.e. what condition the best helper needs to meet, how to choose the helper and when to cooperate. According to the cooperative participation manner of the helper, the helper selection method can be divided into three categories: the sender-specified method, the recipient-specified method, and the helper contention method.

The typical cooperative MAC protocols of sender-specified helper include the CD-MAC protocol [1], the CoopMAC protocol [7], the rDCF protocol [8], the adaptive distributed cooperative MAC (ADC-MAC) protocol [12], the relay-contention-free cooperative MAC (RCF-CMAC) [13], the cooperative access with relay's data (CARD) protocol [14] and the

busy tone based cooperative MAC (BTAC) protocol [15]. In the CD-MAC protocol [1], according to overhearing the data packet transmissions of neighboring nodes, the sender determines the SNR between itself and the potential helpers, and then selects the neighboring node with the highest SNR as the helper and establishes the cooperation table. The sender binds with the helper until the associated cooperative transmission fails or the sender finds that there exists a helper with a better link quality. The drawbacks of the protocol are as follows. Firstly, the cooperation table consumes large storage overhead. Secondly, the information of the helpers cannot update timely. Thirdly, the data rate from the helper to the recipient cannot be guaranteed. Therefore, it cannot achieve the best cooperation gain. In the ADC-MAC protocol [12], each node also needs to establish a cooperation table, and uses the shortest path algorithm to select the helper between itself and its recipient and designates the helper in the request-to-send (RTS) packet. If the received SNRs of the packets transmitted from the helper to the sender and the recipient are higher than a given threshold, the helper sends a helper-clear-to-send (HCTS) packet to indicate its cooperation willing. The sender determines whether the helper can cooperate for transmission according to the instantaneous received SNRs from the sender to the helper and from the recipient to the helper recorded in the HCTS packet. If the helper is able to cooperate, the sender adopts the cooperation method to transmit the data packet. Otherwise, the sender transmits the data packet to its recipient directly. However, the protocol consumes much more communication overhead because each node periodically broadcasts heartbeat packets, and does not maximize the cooperation performance improvement because the only helper nominated by the sender may decrease the cooperation performance in actual cooperative relaying. In the RCF-CMAC protocol [13], a sender preselects two optimal helper candidates through its local relay information table, and sets different priorities to them in cooperative RTS (CRTS) packet according to relay efficiency that reflects the level of its saved time. Through overhearing the handshakes between the sender and the recipient, the two helper candidates can acquire instantaneous transmission rate information among the sender, the recipient and themselves. Then they orderly declare to become the final relay based on their priorities and associated instantaneous transmission rate information. Therefore, the proposed protocol can rapidly select the optimal relay under current channel quality without contention collisions to cooperatively transmit data packets from all the potential relays, and consequently improve cooperative multiple access performance.

One of typical cooperative MAC protocols of recipient-specified helper is the OXIDE protocol [16]. In OXIDE protocol, each node maintains a relay table, which records the potential helper's ID, the time of last frame transmission heard from the helper, the signal SNR from the node to the helper, and the number of cooperative transmission failures of the helper. When this number exceeds a predefined threshold, the corresponding entry is removed from the relay table. When the sender fails to transmit the data packet to the recipient directly, the recipient chooses the node with the maximum mutual information of the cooperative transmission from the relay table as the helper, and sends a claim for cooperation (CFC) packet to inform the sender of the transmission failure and notify the helper to proceed with cooperative transmission. The protocol only guarantees that the link quality from the helper to the recipient is the best, but it cannot ensure the link quality from the sender to the helper. As a result, the helper may not receive the data packet correctly from the sender, thus leading to the cooperative transmission failure.

Both the method of the sender-specified helper and the method of the recipient-specified helper need to establish and maintain a relay table, which results in the possible outdated cooperation information and lots of overhead.

Recently, more and more cooperative MAC protocols use the third helper selection method, that is, the helper contention method [4][11][17-19]. In the 2rcMAC protocol [11], helpers are divided into eight priorities. The helpers with different priorities choose different time to send the cooperation information. And the best helper can be determined based on its transmission time at the end of the cooperative contention phase. However, the lower priority helpers also need to transmit their cooperation information, causing the channel resource wastage. Moreover, multiple helpers may be selected to relay the data packet at the same time, which requires strict time synchronization and higher power consumption. The cooperative MAC-aggregation (CoopMACA) protocol [18] uses the packet aggregation mechanism to improve the throughput performance. Its helper selection procedure includes classification round, priority round and contention round. The classification round is to distinguish the helpers with packet to send and those without packet to send. The helpers with data packet to send take precedence to enter the priority round. In the priority round, the helpers with the highest data rates to the sender and the recipient can be selected, and then in the contention round the best unique helper is determined from all the highest priority helpers. Finally, the selected helper with packet to send adopts the packet aggregation mechanism to carry out the cooperative transmission, i.e., the selected helper aggregates its data packet with the sender's data packet and sends the aggregated data packet to the recipient. In the case that multiple helpers are selected, cooperative transmission cannot be used and the sender directly transmits the data packet to the recipient. Therefore, the packet aggregation mechanism also cannot be used, which results in the channel wastage of cooperation handshakes and higher cooperation overhead. In addition, the protocol first chooses all the nodes with packet to send as the helper candidates, and then considers the cooperative performance improvement. Therefore, the cooperative multiple access performance is always not the best and is likely to be worse. In the CoopGeo protocol [19], every node contends the cooperation right according to geographic information and does not need cooperative control packet handshakes. The helper in the best cooperative location between the sender and its recipient has the counter with the smallest value and can relay the data packet earlier. Therefore, it can avoid control packet collisions and have less overhead. However, it is possible that the counter values of multiple helpers are almost the same, leading to the cooperative transmission failure.

3. Network Model

In a multihop wireless network, all nodes are randomly distributed in a given area and share one wireless symmetrical channel. Each node exchanges control packets and data packets on the channel using a half-duplex transceiver with a fixed transmission power. If there is no packet to send, each node keeps sensing the channel.

The PHY layer of each node provides mutirate transmission capability. For simplicity, we consider the IEEE 802.11b PHY layer [20] in this paper, which can support multirate transmission of 1, 2, 5.5 and 11 Mbps. Each node sends RTS, CTS and acknowledgment (ACK) packets with basic transmission rate of 1 Mbps, and sends data packets with the maximum transmission rate to its recipient. Each node can calculate the corresponding data rate satisfying a certain BER between it and its neighboring node by means of the reception of the neighboring node's packets [7]. If multiple helpers simultaneously begin to transmit the same data packet to a recipient, the recipient can correctly receive the data packet.

4. CRP-CMAC Protocol

The CRP-CMAC protocol uses the high data rate helper to help the low data rate sender transmit data packets and thus obtain cooperation gain. It includes three phases, i.e. reservation phase, helper selection phase and data packet transmission phase. Here, the helper selection phase is further divided into the priority differentiation phase (PDP) and the contention resolution phase (CRP) of the same priority helpers, which can promptly select the unique optimal helper to improve the cooperation efficiency. The proposed protocol also adopts packet piggyback mechanism, i.e. the high data rate helper with packet to send can piggyback its reservation information in its relayed data packet for the sender and then send its data packet to its recipient immediately after the end of cooperative data packet transmission without further reservation handshakes. Here, the recipient of the sender and that of the helper can be different. Therefore, the mechanism greatly decreases the reservation overhead, provides rapid channel access for the helpers and further improves multiple access performance.

4.1 Reservation Phase

When a sender S senses the channel idle, it sends an RTS packet to its recipient D with basic data rate of 1 Mbps according to 802.11 DCF [20]. On receiving the RTS packet correctly, the recipient replies to its sender with a CTS packet. By the RTS/CTS handshakes, both the sender and its recipient know the highest data rate R_{SD} that they can support between each other. And other neighboring nodes in the network that successfully receive and decode both RTS and CTS packets can also estimate the highest data rate between the sender and it (i.e. R_{SH}) and the highest data rate between it and the recipient (i.e. R_{HD}). If R_{SD} is in the high data rate group, i.e., 11 Mbps or 5.5 Mbps, the sender transmits data packet to the recipient directly, as shown in **Fig. 1**. Otherwise, it adopts cooperative transmission to send the data packet and then initiates the helper selection phase.
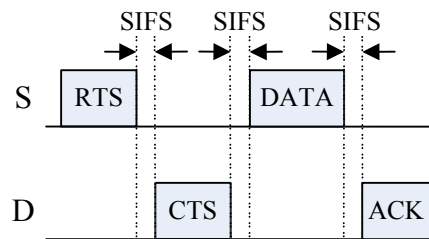

Fig. 1. Direct transmission mode when R_{SD} is high

4.2 Helper Selection Phase

Helper selection phase includes two parts, i.e. priority differentiation phase and contention resolution phase of the same priority helpers.

(1) Priority differentiation phase

If the helper does not receive the data packet during the interval SIFS+τ after it received CTS packet, it indicates that the sender is unable to support high data rate transmission to its recipient. Therefore, the helper needs to initiate cooperative transmission and starts the priority differentiation phase. The reserved τ is for the helper to make sure whether to cooperate and avoid the collisions of cooperative contention transmission and direct data packet transmission.

In the priority differentiation phase shown in **Fig. 2**, all helpers are divided into 12 priorities in turn based on the following two factors for cooperative participation. One is the values of R_{SH} and R_{HD}, and the other is whether the helper has packet to send. The helper with higher priority can choose the earlier minislot to send its busy tone. The 1st, 2nd, 3rd and 4th priority helpers are those with packet to send, and higher R_{SH} and R_{HD}. The 5th, 6th, 7th and 8th priority helpers are those without packet to send, and with higher R_{SH} and R_{HD}. The 9th and 10th priority helpers are those with packet to send, and lower R_{SH} and higher R_{HD}. The 11th and 12th priority helpers are those with lower R_{SH} and higher R_{HD}, or higher R_{SH} and lower R_{HD}. As shown in **Fig. 2**, if both R_{SH} and R_{HD} are 11 Mbps, and the helper has packet to send, it belongs to the first priority. The possibility of R_{SH} and R_{HD} for the first ten priorities is unique. However, the last two priorities have two possible cases because both the cases have the same cooperation efficiency. For example, the 11th priority contains the cases of R_{SH}=2 Mbps and R_{HD}=11 Mbps, and R_{SH}=11 Mbps and R_{HD}=2 Mbps. Each priority contains a minislot with the interval δ.

Based on the overhearing of RTS and CTS packets, each helper estimates the highest data rates R_{SH} and R_{HD} that it can support, and chooses the minislot of the corresponding priority to send a busy tone of interval δ. Every helper needs to sense the channel before its predefined busy tone transmission. If the helper senses the busy tone transmission before its predefined busy tone transmission, it will not send its busy tone and withdraw from its cooperation contention because of the already-succeeded helper with higher priority. Priority differentiation phase ends once a helper sends its busy tone, and the contention resolution phase immediately starts since next minislot. Therefore, priority differentiation phase has the minimum interval δ, maximum interval 12δ, and average interval 6.5δ.

For instance, a helper R_1 with packet to send estimates that R_{SH} is 11 Mbps and R_{HD} is 5.5 Mbps, and does not sense any busy tone before its upcoming busy tone transmission. Then it sends its busy tone in the third minislot. Other helpers sense the busy tone and cancel their upcoming busy tone transmission. Therefore, the helper R_1 gets the opportunity to enter the contention resolution phase to contend the cooperation right.
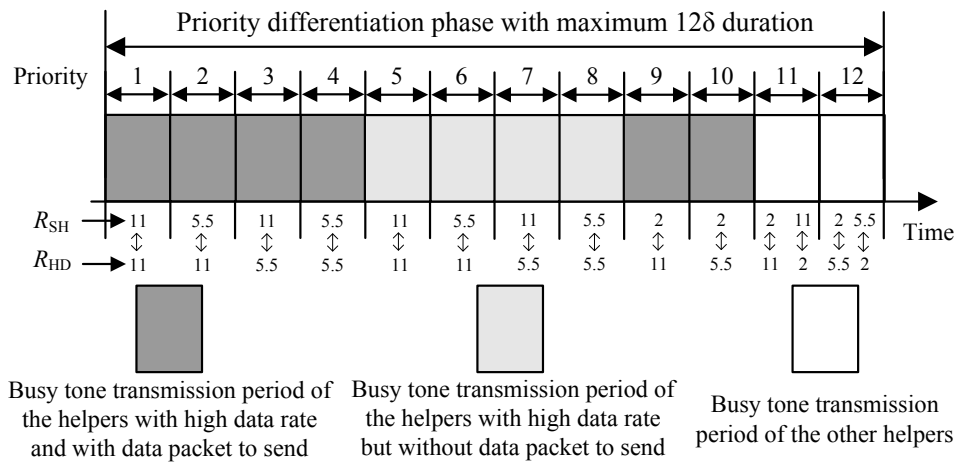

Fig. 2. Priority differentiation phase

(2) Contention resolution phase

It is possible that there are multiple helpers with the same priority that choose the same minislot to simultaneously send their busy tones. In order to avoid the possible collisions caused by their concurrent cooperative packet transmissions and guarantee the application of

packet piggyback mechanism, the contention resolution phase (CRP) of the same priority helpers is employed in our protocol. As shown in **Fig. 3**, it includes k round contention resolution (k-CR) procedures with at most M contention minislots every round.

All the successful helpers in the priority differentiation phase randomly choose one of M minislots (say the mth minislot, $1 \leq m \leq M$) in the first round to begin to send a busy tone with the length of n minislots, where $1 \leq n \leq M$ and $m+n-1 \leq M$. Before the selected minislots, they sense the channel. If a helper (say the helper H_5 shown in **Fig. 3**) senses the busy tone before its busy tone transmission, it loses the contention and cancels its scheduled busy tone transmission. After the helpers that succeed to send their busy tones in the earliest minislot of the round complete their busy tone transmissions, they observe the channel for a minislot. If they sense the busy tone, they abandon their next round contention (say the helper H_4 shown in **Fig. 3**). Therefore, the mechanism can guarantee that the helper that sends the longest busy tone earlier wins the round. If the M minislots of the round do not end at the end of the busy tone transmissions (i.e. $m+n-1<M$ or $m+n \leq M$), the helper observe one minislot to determine whether there is busy tone. If it does not sense the busy tone, it ends this round contention immediately and starts the next round contention process (say the helper H_1, H_2 and H_3 in the first round shown in **Fig. 3**). If the M minislots of the round end at the end of the busy tone transmissions (i.e. $m+n-1=M$), the helper do not need to observe the channel and directly enter into the next round contention process (say the helper H_1 and H_2 in the second round shown in **Fig. 3**). All the successful helpers in the last round repeat the same procedure in the next round until the end of the kth round contention.
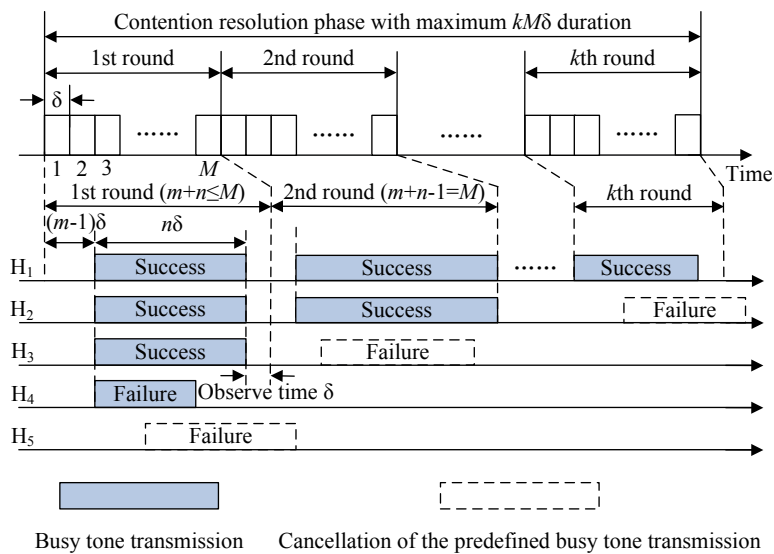

Fig. 3. Contention resolution phase

Fig. 4 shows an example of the contention resolution phase, where k=3 and M=5. In the first round contention resolution process, the earliest busy tone transmission starts from the third minislot (i.e. m=3) and then the longest busy tone has the length of two minislots (i.e. n=2). The helpers that send busy tone with two minislots long starting from the third minislot win the first round contention, and after they observe the channel for a minislot and do not sense the busy tone transmitted by other helpers, they enter into the second contention resolution process. Meanwhile, if the helpers send the busy tone with one minislot long starting from the third minislot, they sense the channel busy and then quit the contention. If the helpers select

the fourth minislot or later minislot to send their busy tone, they sense the busy tone transmitted by other helpers and cancel their scheduled busy tone transmissions. The second round contention resolution process is similar to the first round. If $m+n-1=M$, all successful helpers do not need to observe the channel for one minislot and immediately enter into the third round contention resolution process. In the third round contention resolution process, the helpers that send the earliest busy tone do not sense the busy tone transmitted by other helpers after the end of their busy tone transmission and then the round ends after the fourth minislot.
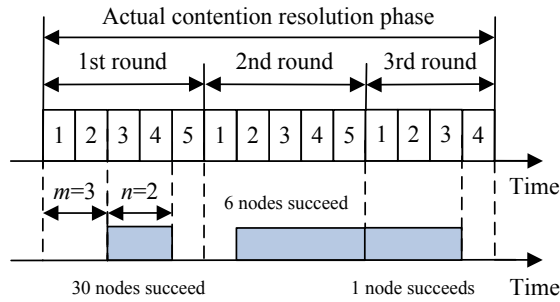

Fig. 4. An example of the contention resolution phase.

Table 1 shows the probability of selecting the unique helper p_{UH} under different k and M using the k-CR scheme, where N is the number of contending nodes. **Fig. 5** shows the impact of k and M on the probability of selecting the unique helper p_{UH}. We can see that the probability of only one helper that wins the cooperation right at the end of the kth round contention is nearly equal to 1 if the values of k and M are enough high. For example, when $k=3$ and $M=5$, the probability of selecting the unique helper is 99.08% for 100 contending nodes. Therefore, the proposed k-CR scheme can guarantee selecting the unique optimal helper to apply the packet piggyback mechanism and then further improve cooperation efficiency.

Table 1. Probability of selecting the unique helper under different k and M

N	k	p_{UH}							
		$M=2$	$M=3$	$M=4$	$M=5$	$M=6$	$M=8$	$M=10$	$M=12$
12	1	0.128978	0.465591	0.660474	0.773230	0.837623	0.903546	0.938189	0.956417
	2	0.628408	0.888259	0.954327	0.979453	0.989043	0.995501	0.998205	0.999077
	3	0.850622	0.977157	0.993798	0.998112	0.999258	0.999862	0.999948	0.999978
	4	0.946567	0.995350	0.999250	0.999830	0.999952	0.999998	0.999999	0.999999
	5	0.981695	0.999070	0.999961	0.999984	0.999997	1.000000	1.000000	1.000000
	6	0.993613	0.999800	0.999995	0.999999	0.999999	1.000000	1.000000	1.000000
	7	0.997940	0.999961	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	8	0.998592	0.999991	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	9	0.999382	0.999999	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
25	1	0.006056	0.171420	0.403763	0.578775	0.690559	0.814012	0.878853	0.914503
	2	0.402453	0.810441	0.918417	0.961648	0.979276	0.993343	0.996487	0.998165
	3	0.763435	0.961113	0.988352	0.996537	0.998586	0.999711	0.999894	0.999962
	4	0.909660	0.992103	0.998704	0.999676	0.999910	0.999972	0.999997	0.999999
	5	0.972113	0.998375	0.999908	0.999973	0.999994	1.000000	1.000000	1.000000
	6	0.990865	0.999679	0.999948	0.999997	0.999999	1.000000	1.000000	1.000000

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	7	0.997000	0.999931	0.999974	1.000000	1.000000	1.000000	1.000000	1.000000
	8	0.997836	0.999985	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	9	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
50	1	0.000000	0.017354	0.131664	0.308487	0.458747	0.656987	0.770386	0.836112
	2	0.132342	0.699480	0.871915	0.935596	0.963569	0.987262	0.993417	0.996503
	3	0.631641	0.938025	0.983191	0.994144	0.997505	0.999529	0.999813	0.999923
	4	0.846719	0.987367	0.997798	0.999469	0.999836	0.999967	0.999996	0.999999
	5	0.954008	0.997407	0.999561	0.999949	0.999989	1.000000	1.000000	1.000000
	6	0.983517	0.999471	0.999962	0.999996	0.999999	1.000000	1.000000	1.000000
	7	0.993899	0.999889	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	8	0.997310	0.999980	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	9	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
100	1	0.000000	0.000085	0.009682	0.071354	0.180796	0.409646	0.581126	0.691345
	2	0.007502	0.501092	0.800241	0.900004	0.941601	0.978980	0.988228	0.993452
	3	0.465655	0.895467	0.972635	0.990834	0.996021	0.999064	0.999602	0.999844
	4	0.763372	0.978393	0.996045	0.999181	0.999721	0.999974	0.999987	0.999995
	5	0.918000	0.995712	0.999217	0.999924	0.999970	1.000000	1.000000	1.000000
	6	0.963637	0.999110	0.999966	0.999992	0.999999	1.000000	1.000000	1.000000
	7	0.983320	0.999829	0.999995	0.999999	1.000000	1.000000	1.000000	1.000000
	8	0.993552	0.999965	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	9	0.999924	0.999990	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
200	1	0.000000	0.000000	0.000000	0.002374	0.020139	0.137583	0.312234	0.460475
	2	0.000000	0.226396	0.665948	0.838078	0.911316	0.964855	0.980726	0.988782
	3	0.149577	0.826535	0.955258	0.985364	0.993982	0.998463	0.999432	0.999759
	4	0.636525	0.964297	0.992557	0.998646	0.999612	1.000000	1.000000	1.000000
	5	0.865725	0.992791	0.997908	0.999867	0.999962	1.000000	1.000000	1.000000
	6	0.948973	0.998569	0.999472	0.999986	0.999999	1.000000	1.000000	1.000000
	7	0.966438	0.999663	0.999994	0.999998	1.000000	1.000000	1.000000	1.000000
	8	0.992820	0.999933	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
	9	1.000000	0.999990	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
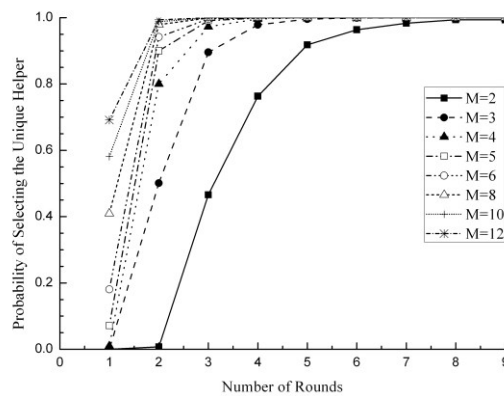
Fig. 5. Impact of k and M on the probability of selecting the unique helper p_{UH}

Table 2 shows the comparison of p_{UH} using the k-CR and k-EC schemes under different N and k. Here, the results of the k-EC scheme are from [21]. From the table, under the same k and M (i.e. m in the k-EC scheme), the k-CR scheme has higher probability to select the unique helper than the k-EC scheme.

Table 2. Comparison of p_{UH} between k-CR and k-EC schemes

N	k	p_{UH}	
		k-CR (M=3)	k-EC (m=3)
50	4	0.9874	0.7221
	5	0.9974	0.9008
	6	0.9995	0.9655
	7	0.9999	0.9883
	8	1.0000	0.9963
	9	1.0000	0.9988
100	4	0.9784	0.5037
	5	0.9957	0.8084
	6	0.9991	0.9322
	7	0.9998	0.9767
	8	1.0000	0.9923
	9	1.0000	0.9975

4.3 Data Packet Transmission Phase

Based on the different helper selection results, the data packet transmission phase is divided into four cases as follows.

(1) As shown in **Fig. 6**, if there is no helper existed in the network after the helper selection phase, the sender transmits its data packet with the data rate of R_{SD} to its recipient directly.
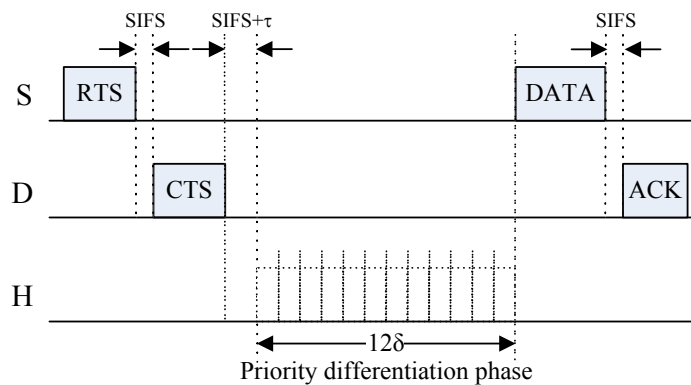
Fig. 6. The case of no helper for cooperative transmission

(2) If the successful helpers support high data rate and have data packets to send (i.e., the helper with priority 1, 2, 3, 4, 9 or 10), the packet piggyback mechanism can be used. However, it needs to ensure that only one best helper wins during the helper selection phase. As shown in **Fig. 7**, to achieve this, every successful helper needs to send a help-to-send (HTS) packet to

the sender with data rate of R_{SH} at the end of the helper selection phase. If the sender successfully receives and decodes the HTS packet, it indicates that only one helper wins during the helper selection phase and the packet piggyback mechanism can be used. The information of the packet piggyback mechanism and the total transmission time for the entire data packet transmission are designated in the data packet transmitted by the sender with the data rate of R_{SH}. After the helper receives the data packet from the sender, it relays the data packet to the recipient of the sender with the data rate of R_{HD}, and then transmits its data packet to its recipient. The recipients of the sender and the helper in turn reply with an ACK packet to their corresponding senders, respectively.
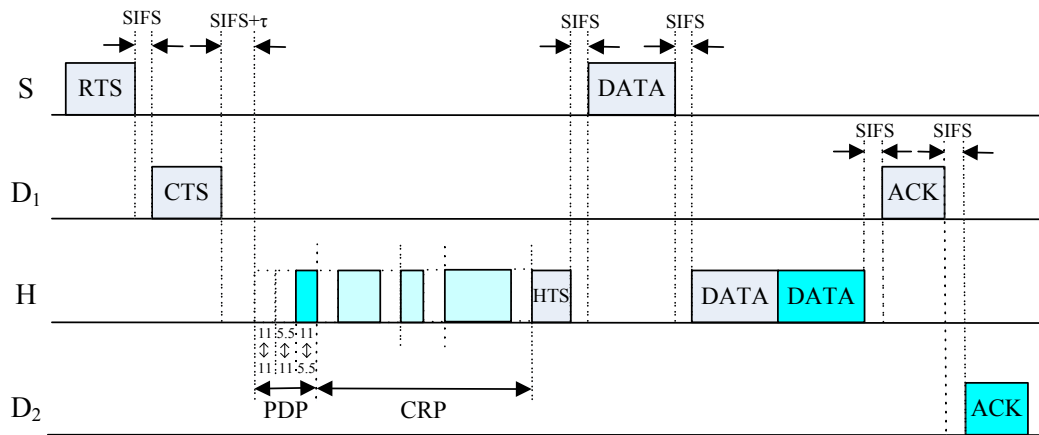
Fig. 7. The case of only one successful high data rate helper with packet to send

(3) In the case (2), as shown in **Fig. 8**, if the sender is unable to decode the HTS packet, it indicates that multiple helpers succeed during the helper selection phase, and they send their HTS packets simultaneously resulting in the collisions at the sender. In this case, the packet piggyback mechanism cannot be used. Therefore, the sender transmits the data packet to all succeeded helpers with the data rate of R_{SH} and then the helpers relay it to the recipient with the data rate of R_{HD}. The recipient replies to the sender with an ACK packet after it successfully received the data packet.
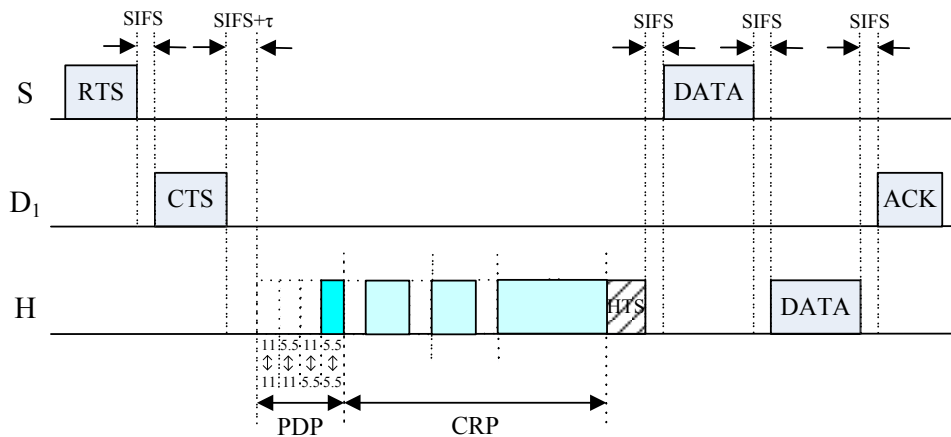

Fig. 8. The case of multiple successful high data rate helpers with packet to send

(4) If the successful helpers support high data rate and do not have data packets to send (i.e., the helper with priority 5, 6, 7, 8, 11 or 12), the packet piggyback mechanism cannot be used. The sender transmits its data packet to the helpers with the data rate of R_{SH} immediately after the end of the helper selection phase, and then the helpers relay the data packet to the recipient with the data rate of R_{HD}. The recipient replies with an ACK packet to the sender after it successfully received the data packet. The transmission process is shown in **Fig. 9**.
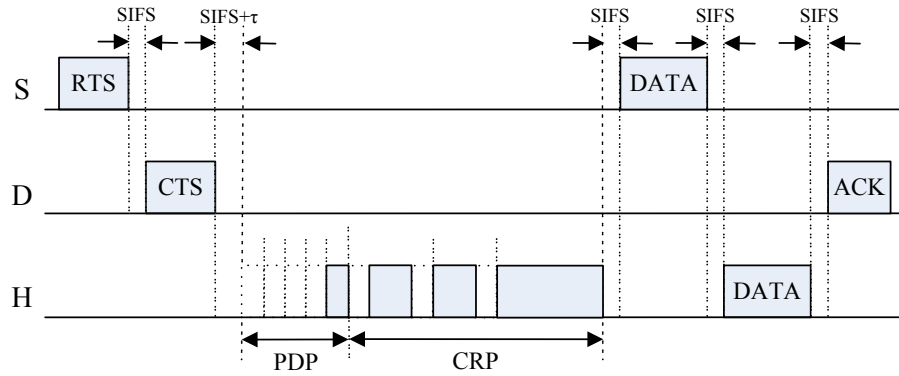
Fig. 9. The case of high data rate helper(s) without packet to send

5. Performance Evaluation

In this section, we use C programming language to simulate the performance of the CRP-CMAC protocol, and make performance comparison with the 2rcMAC and CoopMACA protocols. In the simulation, we take the throughput, saturation throughput and delay as the performance metrics to evaluate multiple access performance. Herein, the throughput is defined as all the successfully transmitted data packets in bits per second, the saturation throughput is defined as the successfully transmitted data packets in bits per second, given that each node always has a packet to transmit, and the delay is defined as the mean time interval for a data packet from the time of its generation to the time of its successful reception by its recipient.

5.1 Simulation Environment

In the simulation, two typical wireless networks with N nodes, namely a WLAN and an ad hoc network, are considered. All nodes are randomly distributed in a circle area with a radius of 100 m in the network. In the WLAN, an access point (AP) is located at the center of the circle area and all the sender's recipients are the AP, whereas in the ad hoc network, the recipient of a sender is randomly selected from its neighboring nodes. Packets are transmitted at different rates, depending on the distance between the sender and the recipient. On the condition that the path loss exponent is 3 and the BER is lower than 10^{-5}, the maximum transmission distances with data rate 11, 5.5, 2 and 1 Mbps are 48.2, 67.1, 74.7 and 100 m, respectively [7]. Each node generates data packets with fixed length according to a Poisson distribution with packet arrival rate λ_0. By default, the length of a data packet L_{PKT} is 1 kB and N is 100. The simulation parameters are set in **Table 3**. Here, δ is set 10 μs by considering the physical layer implementation according to the CoopMACA protocol [18] and k-EC scheme [21]. For the purpose of accuracy, we take the average simulation results over 50 random network

topologies as the final results. To fully reflect protocol performance, we only take into consideration the transmission failures caused by packet collisions, rather than by channel errors.

Table 3. Simulation parameters

Parameter	Value
MAC header	272 bits
PHY header	192 bits
Data rate for MAC and PHY headers, RTS, CTS, HTS and ACK packets	1 Mbps
RTS	160 bits
CTS/ACK	112 bits
HTS	112 bits
SIFS/τ	10 μs
DIFS	50 μs
δ	10 μs
Slot time	20 μs
k	3
M	5
Max. number of retransmissions	6
Packet lifetime	0.512 s

5.2 Performance Comparison under Different Network Environment

Fig. 10 and **Fig. 11** show the performance comparison of the CRP-CMAC, 802.11 DCF, CoopMACA and 2rcMAC protocols with the variation of packet arrival rate in the WLAN and ad hoc network. The figures show that all cooperative MAC protocols have better performance than the noncooperative MAC protocol (i.e. 802.11 DCF) due to their cooperation gain, and the performance of the CRP-CMAC protocol is obviously better than that of the 802.11 DCF, CoopMACA and 2rcMAC protocols in two network environment. In the WLAN environment, the maximum throughput of the CRP-CMAC is 74%, 36.1% and 15% higher than those of the 802.11 DCF, CoopMACA and 2rcMAC, respectively. In the ad hoc network environment, its maximum throughput is 82.6%, 37.6% and 46.3% higher than those of the 802.11 DCF, CoopMACA and 2rcMAC, respectively. This is because CRP-CMAC adopts more efficient helper selection mechanism and packet piggyback mechanism to improve transmission efficiency. In the proposed protocol, the priority differentiation phase can end in advance as long as one or multiple helpers with the higher priority participate in the contention. Therefore, CRP-CMAC has the helper selection phase with the maximum time of 27δ, the minimum time of 7δ and the average time of 17δ. The helper selection process of 2rcMAC consumes a fixed time of 56δ. In addition, it needs to initiate RTS/CTS handshakes for each data packet. As a result, it costs more overhead than CRP-CMAC. CoopMACA can adopt the packet aggregation mechanism only when one helper wins the cooperation transmission right. Otherwise, it use direct transmission mode, which consumes more cooperation overhead and does not improve the data rate from the sender to the recipient. It is most likely that multiple helpers will succeed during its 3-round contention resolution procedure according to the k-EC

scheme [21]. What is more, it first selects the helpers with packet to send, rather than the helpers with the best cooperation performance. Therefore, its performance is the worst. Compared to the CoopMACA and 2rcMAC, CRP-CMAC has rapid helper selection process to most likely select the best helper, and uses the packet piggyback mechanism to decrease reservation overhead, resulting in its highest throughput and lowest average packet delay among the three cooperative MAC protocols.
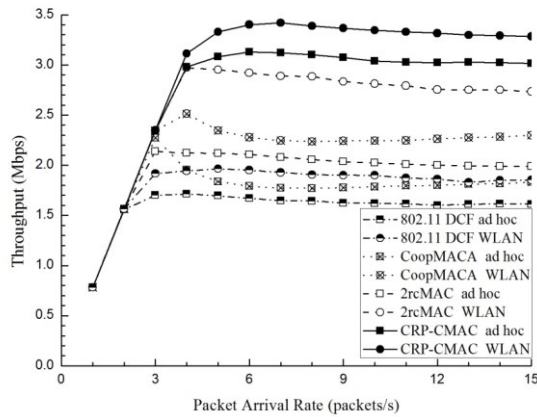
Fig. 10. Throughput comparison under different network environment
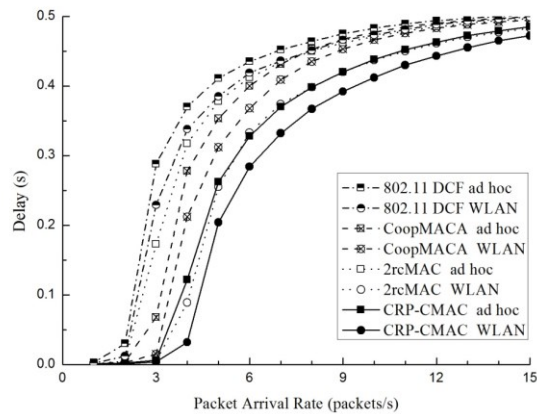
Fig. 11. Packet delay comparison under different network environment

From the figures, we can also see that the performance of the CRP-CMAC, 802.11 DCF, CoopMACA and 2rcMAC protocols with the variation of packet arrival rate in the WLAN is better than that in the ad hoc network. This is because different communication node pairs in the ad hoc network greatly increase the probability of packet collisions. It is also obvious that CRP-CMAC greatly outperforms 802.11 DCF, CoopMACA and 2rcMAC in the ad hoc network compared with in the WLAN. As mentioned before, in CRP-CMAC, the data packets of the sender and its helper are separately transmitted and their recipients can be different. Therefore, its packet piggyback mechanism can well apply to both the WLAN and ad hoc network. However, the packet aggregation mechanism adopted by CoopMACA cannot be

well applied to the ad hoc network because it requires that the recipients of data packets of the sender and the helper are the same, which leads to the worse performance in the ad hoc network than in the WLAN. In addition, CRP-CMAC has smaller packet delay than 802.11 DCF, CoopMACA and 2rcMAC because it can access cooperative transmission more quickly and its selected helper(s) can support higher data rate to further decrease the service time for each data packet.

5.3 Impact of *N* on Saturation Throughput

Fig. 12 shows the impact of the number of nodes N in the network on the saturation throughputs of the CRP-CMAC, CoopMACA and 2rcMAC protocols at 10 Mbps offered load in the WLAN and ad hoc network environment. It is also obvious that the saturation throughput of CRP-CMAC is higher than those of 2rcMAC and CoopMACA under different network environment and N. With the increase of N, all their saturation throughputs increase at first and then decrease slightly. This is because at smaller N, fewer potential helpers can participate in the cooperative contention and complete the cooperative transmissions with higher cooperation efficiency, and at larger N, the contention collisions of helpers become larger and the probability of selecting the unique helper becomes smaller. For CoopMACA, the k-EC scheme with k=3 and m=3 has smaller probability of selecting the unique helper, resulting in that its saturation throughput decreases a lot when N is large enough.
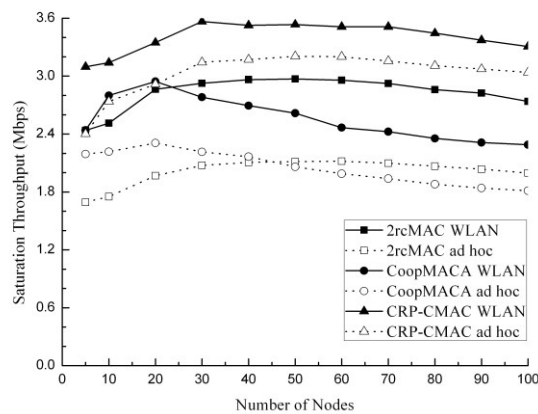

Fig. 12. Saturation throughput under different number of nodes

5.4 Impact of *k* and *M* on Saturation Throughput

Fig. 13 shows the impact of k and M on the saturation throughput of the CRP-CMAC protocol in the WLAN environment. At the same M, with the increase of k, its saturation throughput increases at first and then decreases due to the tradeoff between the throughput improvement caused by the packet piggyback mechanism and the cooperation overhead caused by the consumed minislots during the helper selection phase. That is to say, with the increase of k, the probability of selecting the unique helper becomes larger and then the packet piggyback mechanism can improves the throughput. On the other hand, this occupies more minislots during the helper selection phase and increases the cooperation overhead, resulting in lower throughput.
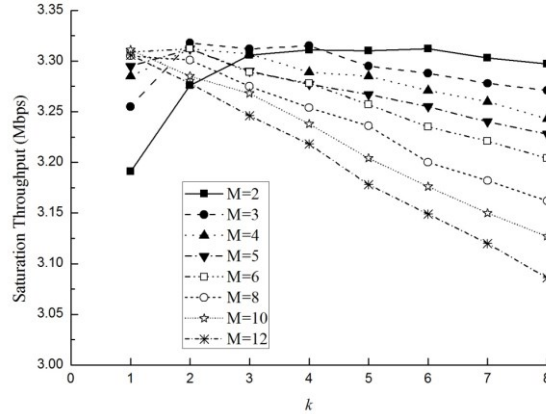
Fig. 13. Saturation throughput under different k and M

5.5 Impact of Packet Length L_{PKT} on Network Performance

Fig. 14 and **Fig. 15** show the impact of packet length L_{PKT} on the performance of the CRP-CMAC, CoopMACA and 2rcMAC protocols in the WLAN and ad hoc network environment. As shown in the figures, with the increase of L_{PKT}, their throughputs increase and their delay decrease. This is because with the increase of L_{PKT}, each node can send more data information bits in the presence of each successful channel reservation. Moreover, the performance of CRP-CMAC is obviously better than that of other protocols under different L_{PKT} because it can promptly select the unique best helper or the best helpers, and its packet piggyback mechanism can effectively decreases the reservation overhead. When L_{PKT} is 2 kB, CRP-CMAC achieves 31.4% and 12.8% throughput gain than CoopMACA and 2rcMAC in the WLAN environment, and 40.7% and 39.4% throughput gain in the ad hoc network environment, respectively. The above results show that CRP-CMAC can well apply to both WLANs and ad hoc networks.
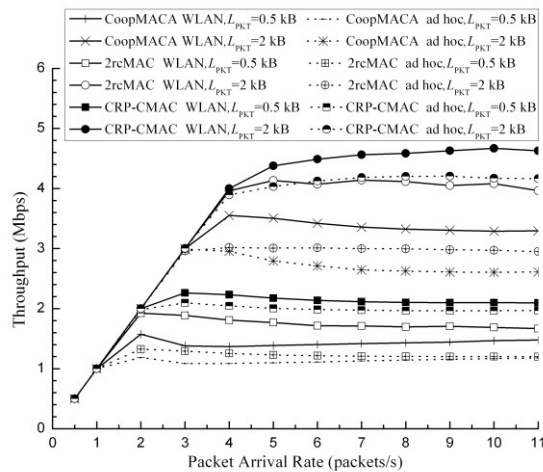

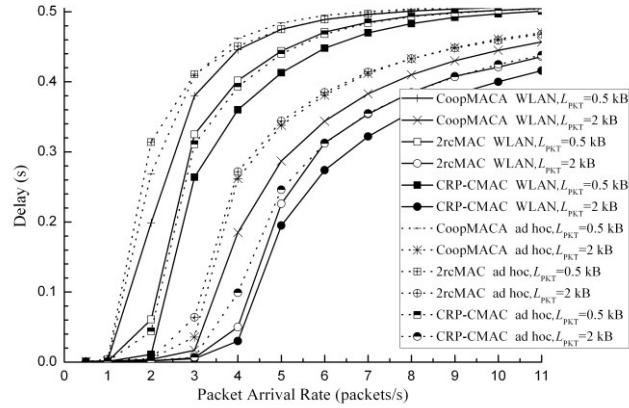**Fig. 14.** Throughput under different packet length

Fig. 15. Packet delay under different packet length

5.6 Impact of δ on Network Performance in Ad Hoc Network Environment

Fig. 16 and **Fig. 17** show the performance comparison of the CRP-CMAC, CoopMACA and 2rcMAC protocols under different δ in ad hoc network environment. Here, δ is set 1, 5 and 10 μs. From the figures, δ has a significant influence on the performance of 2rcMAC and slight influence on the performance of CRP-CMAC and CoopMACA, and CRP-CMAC obviously outperforms the other protocols under different δ. This is because the helper selection procedure of CoopMACA, CRP-CMAC and 2rcMAC has an approximate average duration of 9δ, 17δ and 56δ, respectively. At larger packet arrival rate, CoopMACA has the smaller probability of selecting the unique helper and thus has the smaller probability of using its packet aggregation mechanism, resulting in the decrease of its performance. CRP-CMAC has a fairly moderate cooperation overhead, and has at least a probability of 99.08% to select the unique helper to employ packet piggyback mechanism, which efficiently improves its performance.
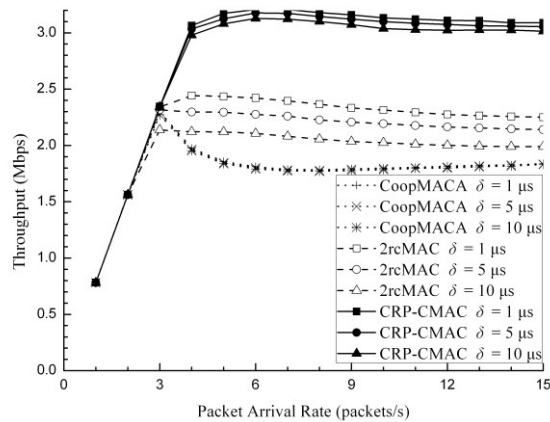

Fig. 16. Throughput under different δ in ad hoc networks

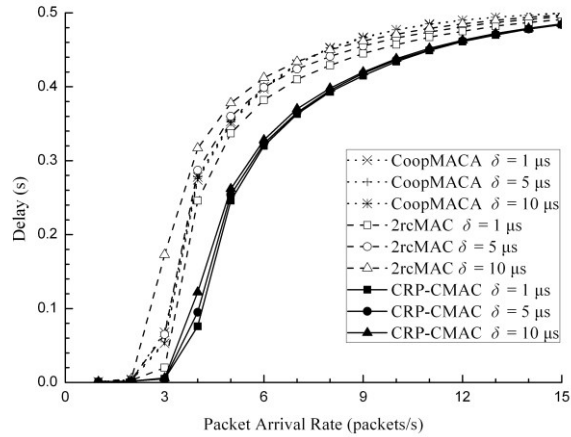**Fig. 17.** Packet delay under different δ in ad hoc networks

6. Conclusion

This paper proposed a novel priority-differentiated cooperative MAC protocol with contention resolution for multihop wireless networks. The proposed protocol adopts efficient priority differentiation scheme and k round contention resolution scheme to rapidly select a unique optimal helper with the most probability and thus improve cooperation efficiency. Meanwhile, it also uses packet piggyback mechanism to reduce reservation overhead, expedite data packet transmission, and then improve protocol performance. Simulation results show that compared to the 802.11 DCF, CoopMACA and 2rcMAC protocols, in the presence of 100 nodes, the proposed protocol achieves a throughput improvement of 74%, 36.1% and 15% in the WLAN environment, and that of 82.6%, 37.6% and 46.3% in the ad hoc network environment, respectively.

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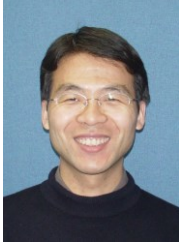
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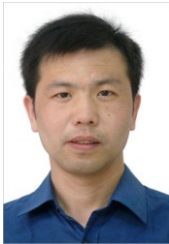
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