Cooperative Medium Access Control in Wireless Networks: the Two-hop Case

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***Abstract*—Cooperative communication has been recently proposed as a powerful means to improve network performance in wireless networks. However, most existing work focuses solely on one-hop source-destination cooperation. In this paper, we propose a novel cooperative MAC mechanism that is specially designed for two-hop cooperation communications where the source node and the destination node cannot hear each other directly. In this case, cooperative communication is operated in a two-hop manner and transmit-diversity is achieved by the reception of the same data packet forwarded through multiple relays towards a single destination. The proposed scheme employs an efficient relay selection algorithm to maximize cooperation benefits and can avoid collision effectively. Numerical results show that compared with the original non-cooperative protocol, significant throughput improvement and access delay reduction have been achieved with our two-hop cooperative MAC mechanism.**

***Index Terms*—two-hop cooperative communication, MAC mechanism, relay selection, performance evaluation.**

I. Introduction

In wireless networks with channel fading, severe signal impairment from transmitter to receiver may cause serious system degradation. In order to overcome these fading problems, cooperative communication techniques, in which spatial diversity gain can be achieved through multi-path transmission diversity, have recently been proposed. As a result, significant improvement in communication reliability and system performance has been demonstrated.

However, a dominant majority of existing work focuses on one-hop source destination cooperation under which a relay node may help retransmitting a packet to the destination node if the direct transmission from source to destination fails [1], [2]. Many newly proposed cooperative schemes allow also transmission of relay nodes no matter the direct link is successful or not. Anyhow, a fundamental assumption for one-hop cooperation communication is that the transmitter can reach the receiver directly and one or more relay nodes exist between the transmitter and the receiver. With this perspective, relay selection and Medium Access Control (MAC) mechanisms are of great importance for cooperative communication.

In the presence of multiple relays, relay selection is critical in order to increase the efficiency of cooperation communications [3]–[6]. The key idea behind relay selection is to create best additional paths between source and destination for achieving transmission diversity. The procedure includes comparing a set of multiple relay nodes which are willing to forward the received information toward the destination and a general method is to select the most appropriate relay(s) to forward information to the receiver [7].

There is also increasing consensus in the research community that MAC protocol design is essential for the evolution of cooperative wireless networks. This work has been addressed in [8]–[11]. However, most of these MAC mechanisms are limited to a single one-hop source-destination pair, extended to two-hop source-relay-destination case when one-hop direct transmission failed or cannot sustain the required transmission. These schemes are not easily applied to a network environment where there are lots of multi-hop source-destination pairs.

In this paper, we propose a cooperative MAC protocol specifically designed for two-hop communications. A salient distinction between this work and existing cooperative MAC protocols is that in our scenario the source node and the destination node cannot hear each other so that no direct communication between source and destination (a two-hop node from the source node) is possible. In other words, communication between source and destination has to be forwarded via relay nodes which are one-hop neighbors of both source and destination. As a consequence, the achieved throughput at the destination node is the two-hop throughput in a multi-hop wireless network.

In the proposed mechanism, implicit acknowledgement (ACK) is introduced in order to improve transmission efficiency. Due to path diversity, upon receiving the same packets from multiple paths, an improved packet delivery rate will be achieved, resulting in more reliable transmission, higher throughput and shorter access delay. We could also combine the data at the corresponding destination, which will achieve a full diversity order and lead to further system performance improvement. In order to achieve relay collision avoidance during the transmission we introduce a link quality based relay selection scheme, without requiring topology information. In this scheme, each node monitors the channels towards its neighbors by HELLO messages and the optimal relay nodes are chosen by this hop-by-hop wireless channel condition.

The rest of the paper is organized as follows. The system model is described in Sec. II. After that the relay selection algorithm is introduced in Sec. III, the proposed cooperative MAC protocol is presented in details in Sec. IV. Throughput and access delay analysis is given in Sec. V, and the performance is evaluated compared with the original schemes in Sec. VI. Finally the paper is concluded in Sec. VII.

II. System Model

In this section we introduce the system model to illustrate how our cooperative protocol works in a two-hop manner. As shown in Fig. 1, the system model consists of a source node, S, a destination node, D, and a few intermediate relay nodes, e.g. R_1, R_2, $R_3 \cdots R_n$, which may be used to forward data packets to the destination node in the cooperative mode. In addition, we consider the system is working in a two-hop manner, which means that relay node $R_i (1 \leq i \leq n)$ is the one-hop neighbor of both source node S and destination node D, D is the two hop neighbor of S, and S cannot directly transmit data packets to D. Each data packet transmission will start from S to D by forwarding of R_i. For simplicity, we assume that all relay nodes are able to hear each other.

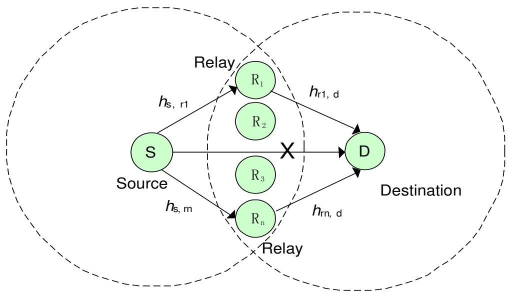

Fig. 1. System model for two-hop cooperative communication.

In the system model, all nodes are working in the promiscuous mode, which means that each node will capture all data packets it receives no matter whether these packets are addressed to this node or not. Additionally, the new MAC protocol adopts implicit ACK method in order to reduce forwarding overhead. Implicit ACK is achieved by overhearing the packet in the forward transmission from the one hop neighbor. For example in Fig 1, S confirms the receipt of its transmission to R_i when one of the relay nodes forwards the packet to D. Furthermore, the channel between any two nodes in our model is assumed to be independent of all other channels.

For each transmission in the two-hop model, S transmits packets to one-hop relay node R_i. Then R_i will forward the packet to D. In order to increase diversity gain, the data packets received from several relay nodes could be combined at the destination. Upon the successful receipt of the DATA packet, an ACK will be returned to S via R_i.

In the following two sections, we will introduce the two-hop cooperative MAC mechanism, which is composed of two steps, relay selection and two-hop medium access scheme.

III. Relay Selection Algorithm

In this section, we develop a relay selection algorithm to obtain optimal spatial diversity gains in cooperative wireless networks. The scheme chooses relay nodes with the best links among all relay candidates according to the combined two hop link quality.

A. The Concept of Multiple Relay Points (MRPs)

The idea of multiple relay points is to obtain benefits from spatial diversity in the network by a higher probability of successful packet transmissions in multiple paths and combine these duplicate transmissions of the same data packets at the intended destination. With this algorithm, each source node in the network independently selects a set of nodes from its one-hop neighborhood, C(S), which could reach the same 2-hop neighbor to retransmit its packets. As illustrated in Fig. 2, this set could be composed of nodes R_1, R_2 ... and R_n for the same destination D_1. Consequently, the set of selected neighbor nodes is called multiple relay point candidates. Furthermore, only part of the multiple relay point candidates (R_1, R_2) participate in packet forwarding, these nodes in this subset R(S) are defined as multiple relay points. The MRP terminology is introduced due to the consideration that at least two relays are needed in order to achieve diversity. Meanwhile, this prevents all the candidates from competing for transmission, thus reducing collision probability.

In addition, all these relay nodes are selected among the one-hop neighbors with a bi-directional link. Therefore, selecting the route through these nodes could automatically avoid the problems associated with data packet transfer on a uni-directional links. Such problems may consist of getting an acknowledgment for data packets at each hop which cannot be received if there is a uni-directional link in the selected route.

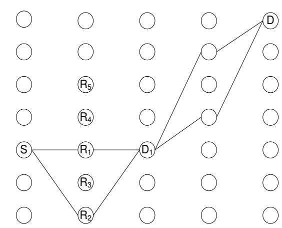

Fig. 2. Multiple relay points in a network.

B. Neighbor Information Acquisition

Under the proposed scheme, each source node must detect channel link condition via its one-hop neighbor nodes with which it has the best path for information relaying. The neighbor information is obtained with the help of HELLO messages which are used to achieve network connectivity and update neighborhood information. More specially, each node periodically broadcasts its HELLO message, containing the information about its neighbors and their link conditions. These control messages are transmitted in the broadcast mode, and received by all one-hop neighbors, but they are not forwarded to further nodes. These HELLO messages help each node to learn the information of its neighbors. According to this information, each source node selects its multiple relay point candidates. In addition, being accompanied by each MRP candidates, there will be an additional value, L_link_quality deriving from link set. It is used to indicate the value of link quality, which is one of the important selection criterions of the MRP.

Upon exchanging the HELLO message with the MRP candidate which contains the link quality information between R_i and D, the source node will know the two-hop overall channel condition between the source and destination node. In other words, direct knowledge on the two-hop neighbors from the view of the one-hop neighbors can be obtained using the information exchange during the connectivity updates. As a consequence, the source node will acquire the channel conditions both from source to relay and relay to destination. These channel information is used for multiple relay point selection.

C. Multiple Relay Points Selection

Cooperative multiple relay points are selected by the source node, which monitors its neighbors and dynamically maintains a table containing the information of MRPs. Since both two hops are important for end-to-end performance, we should take the link quality of both hops into consideration. MRPs is an arbitrary subset R(S) of the MRP candidates C(S) which satisfies the following requirements: the nodes in the subset R(S) are the n nodes[1], where n is the number of MRPs selected, which have the best combined link qualities connecting from source to destination among all the nodes in the relay set R(S) [3], as shown in Fig. 1. For MRP selection, a two-hop path quality indicator, h_i is used which is the combined link quality balancing the two link strength from source to relay and relay to destination node.

$$h_i = \frac{2}{\frac{1}{|a_{si}|^2} + \frac{1}{|a_{id}|^2}} = \frac{2|a_{si}|^2|a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2}, \qquad (1)$$

where a_{si} indicates the link quality between source node S and relay node R_i, a_{id} indicates the link quality between relay node R_i and destination node D. The relay R_i that maximized the function h_i is the one with the *best* end-to-end path between the initial source and the final destination.

Furthermore, according to (1), the MRPs will start to forward the packet in a sequence. Each MRP will obtain its transmission order from the source node by HELLO message exchange. The MRP which maximizes h_i will have the smallest priority number and relay the packet first. And the MRP with second best channel condition will start forwarding after the first one is finished. This process will be introduced in details in the following section.

IV. Cooperative MAC Mechanism Design

In this section, we present the proposed cooperative MAC mechanism based on the system model. Since one relay node could not provide diversity gain, we will mainly focus on the mechanism with more than one MRP. In our scheme, as long as there is more than one MRP to help forward the packets, the system will work in the cooperative mechanism. Otherwise, the system will switch to the enhanced cooperative mechanism with only one relay forwarding traffic from S to D.

A. The Cooperative Mechanism by MRPs

Fig. 3 illustrates the message sequences for the proposed cooperative scheme by two MRPs. Anyhow, the proposed MAC mechanism can be flexibly extended to a larger number of MRPs.

[1]For simplicity, we assume that the number of MRPs is not more than three in our performance evaluation in this paper. However, how to identify the optimal number of MRPs under different channel conditions deserves for further investigation.

As the first step, after the MRPs are selected, each node in the cooperative system model is aware of the number of MRPs. Then node S starts to sense the channel. If the channel is idle for a DIFS time and S has completed the required back-off procedure, a data packet will be sent. As this cooperative communication works in the promiscuous mode, all nodes around S will receive the packets, no matter it is MRP or not. However, only the MRPs will forward the successfully decoded data packets. Since in this cooperative communication area there is no any other transmission except for the two relay transmissions, packets collision will be avoided efficiently. Additionally, Network Allocation Vector(NAV) will prevent potential collision taking place from other nodes rather than S, R_i and D, as described later.

Assuming that both of the MRPs have already correctly received the same data packet from the source node S, then the MRPs will send out the received data packet to the destination after a SIFS time one after another. As we assume that all MRP candidates in the system model can hear each other, they will negotiate with one another on the order of the forwarding. A priority number will be generated according to the channel condition and stored in each MRP. Between two MRPs the one with better channel condition from source to destination h_i will take a smaller priority number and then transmit the packet first (suppose it was R_1). The priority number of the other MRP will increase as the h_i value decreases. During R_1's transmission, R_2 will listen to the channel. If the channel is sensed as *busy* R_2 has to defer its transmission according to the Physical Layer Convergence Procedure (PLCP) header of the ongoing transmitting packet as described in the following subsection. If the channel is sensed as *idle* then R_2 is permitted to transmit the data packet. S will receive the implicit ACK by overhearing the retransmission and decoding the header of the packet to compare with the transmitted packet. If it was the same packet that S just sent out, then S will know the MRP has received the packet. Meanwhile, the data packet is also forwarded to D. It even does not need the back-off mechanism to avoid packet collision because there are only two transmissions and not simultaneously. Extended to more than two MRPs, after the first MRP forwarded the packets, the rest of the MRPs will get this information from detecting the PLCP of the transmitted data, and be aware of that the other MRP with smallest priority number will start transmission.

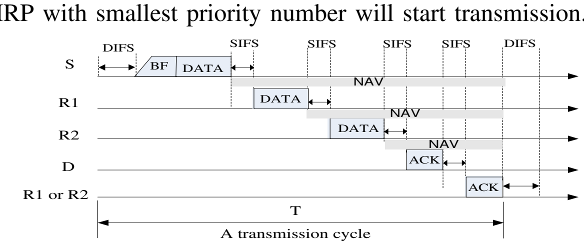

Fig. 3. Cooperative scheme by two MRPs.

After two copies of the data packet from MRPs are received correctly, the reception phase at the destination node will be initiated. Then the MRPs will send ACK to S. Since all nodes are working in the promiscuous mode, D only needs to send an ACK and MRPs will receive it respectively. The MRP with better channel condition h_i will forward the ACK to S first. It will be R_1 as assumed above. Because of the broadcasting nature of wireless communication, S and R_2 will both receive the ACK, upon obtaining one ACK S will initiate the next transmission. However, in case S and R_2 do not receive the ACK during time interval $T_{ACK} + SIFS$, R_2 will send the ACK. Correspondingly, as long as S receives one of the ACKs, the transmission cycle will be finished and S will initiate the next transmission. If S does not get any ACK during time interval $2*(T_{ACK}+\mathit{SIFS})$, another cycle of data transmission has to be initiated.

If the optimal number of MRPs is larger than two, the cooperative mechanism could be easily extended by adjusting the number of DATA and SIFS sub-frames. Consequently, our proposed cooperative MAC mechanism is flexible to accommodate to any number of optimal MRPs.

B. Collision Avoidance

In multi-hop wireless networks, system performance degrades sharply due to packet collision as the number of hops traversed increase. In our cooperative MAC mechanism design, in order to alleviate the hidden terminal effect, NAV has been inherited from the IEEE 802.11 standard. As for the setting of NAV illustrated in Fig. 3, the MRPs have to reserve the maximum time to ensure that its neighbors other than other MRPs maintain silent during the cooperative transmission.

Based on the h_i, the MRP which has the best quality will transmit first. To avoid collision with the first transmitting MRP, the second MRP will read the length of the first transmitted data packet from its PLCP. Therefore, the MRP which detect the channel as busy, will will defer suitable time interval according to the duration filed which derived from the transmitted data length. Even if there are more MRPs, they could check the priority number field to specify the transmission order.

V. Performance Analysis

Similar to the IEEE 802.11 DCF scheme, the system time can be broken down into virtual time slots and each slot is the time interval between the packet sent out from the source node and the packet received at the destination node. The normalized system throughput, denoted by η, is defined as the successfully transmitted payload bits per virtual time unit.

$$\eta = E[B]/E[T], \tag{2}$$

where *E[B]* is the expected number of payload information bits successfully transmitted in a virtual time slot, and *E[T]* is the expected length of a virtual time slot. E[B] can be expressed as:

$$\mathit{E[B]} = P_{succ} * L, \tag{3}$$

where P_{succ} is the probability of a successful transmission and a function of per-hop packet failure probabilities, P_{si}, P_{id}, as described below.

The access delay is defined as the delay between the time when a frame reaches the head of the MAC queue of the source node and the time that the frame is successfully received by the destination (which is two-hop away) node's MAC. With the saturation throughput η, the average access delay of each frame is (L is the average payload length):

$$D = L/\eta. \tag{4}$$

A. Performance in the Original Scheme

When the original 802.11-based scheme used in a two-hop transmission manner[2], the total successful transmission time is the sum of time duration in hop 1 and hop 2, which are calculated respectively.

$$\begin{aligned} E[T^{orig}_{succ}] = T_{hop1} + T_{hop2} = 2*(T_{DATA} + T_{ACK} \\ +\mathit{DIFS} + \mathit{SIFS}) + E[T_{BF_1}] + E[T_{BF_2}]. \end{aligned} \tag{5}$$

In the above equation, T_{DATA}, T_{ACK} represent the time used for transmitting DATA, ACK respectively. T_{BF_1}, T_{BF_2} is the back-off time duration of the transmission starting at the source and relay node respectively. Correspondingly, in the original two-hop scheme we assume that the packet is successfully transmitted by R_1, then the probability of successful transmission in this path will be

$$P^{orig}_{succ} = (1 - P_{s1}) * (1 - P_{1d}). \tag{6}$$

Finally, the saturation throughput η for the original scheme can be obtained by substituting Eqs.(3), (5) and (6) into Eq.(2). And the access delay performance can be obtain by Eq.(4).

B. Performance in the Cooperative Scheme

The performance for the proposed cooperative scheme can be analyzed in a similar way. If there is only one relay, even thought no diversity gain is achieved, the system performance could be improved due to the implicit ACK and saving of back-off time. Without loss of generality, we will study the performance of the cooperative scheme by two MRPs, and then extend the results to more MRPs. According to the MAC design in Fig. 3, the total successful transmission time of an ideal cycle is calculated in a two-hop manner, defined as T^{coop}_{succ}.

$$\begin{aligned} E[T^{coop}_{succ}] = 3*T_{DATA} + 2*T_{ACK} + 4*\mathit{SIFS} + \mathit{DIFS} \\ +E[T_{BF}]. \end{aligned} \tag{7}$$

For the cooperative scheme by two MRPs, let P^{coop}_{succ} denote the probability of successful transmission through the two paths. It can be obtained as

$$\begin{aligned} P^{coop}_{succ} = 1 - [1 - (1 - P_{sr_1}) * (1 - P_{r_1 d})]* \\ [1 - (1 - P_{sr_2}) * (1 - P_{r_2 d})]. \end{aligned} \tag{8}$$

Consequently, the saturation system throughput is able to be obtained by substituting Eqs. (3), (7) and (8) into Eq. (2). In the same way we could obtain the access delay.

According to MAC design of two MRPs cooperation, we could extend the mechanism to more than two MRPs cooperation. The successful transmission time of one ideal cycle by MRPs will be

$$\begin{aligned} E[T^{coop}_{succ}] = (n+1)*T_{DATA} + 2*T_{ACK}+ \\ (n+2)*\mathit{SIFS} + \mathit{DIFS} + E[T_{BF}], \end{aligned} \tag{9}$$

[2]We assume that S, R_i and D are roughly synchronized in the calculation.

where n is the number of MRPs.

The probability of successful transmission through these paths, denoted as P_{succ}^{coop}, will be

$$P_{succ}^{coop} = 1 - \sum_{i=1}^{n} [1 - (1 - P_{si}) * (1 - P_{id})]. \quad (10)$$

VI. Performance Evaluation

In this section, we present the results in comparison with the original 802.11 scheme to illustrate the performance of the proposed cooperative MAC schemes.

We consider a two-hop wireless network for the evaluation of the novel cooperative protocols. The payload length is set to be 500 bytes. The length of the MPDU header is 24 bytes. The physical layer data rate is set to be 54 Mbps. The size of ACK packet is 38 bytes and it is transmitted at the same data rate as the data packet. The overhead of the physical layer header is 20 μs. All the other default parameters in this study are configured according to the IEEE 802.11 standard. Additionally, for simplicity, the packet error rate of all channels are assumed to be identical.

A. System Throughput as PER Varies

According to the analysis in Sec. V, the throughput of our proposed MAC mechanism compared with the original DCF protocol is shown in Fig. 4. We could observe that our proposed cooperative MAC mechanism by MRPs outperforms the original DCF protocol with respect to the obtained two-hop system throughput. This is because the benefits not only come from the reduction of transmission time in the novel cooperative MAC mechanisms but also from the spatial diversity exploited. In the cooperative scheme, due to the time-efficient MAC design and the employment of implicit ACK method, transmission time in a sequence cycle is less than the original two-hop manner.

More specially, the proposed MAC mechanism by one relay node uses least time for a successful transmission cycle. Best system performance is achieved when the channel is error-free. We could observe that it gets highest throughput when the packet error rate is below 0.1. In addition, the new MRP cooperative mechanism by more than one MRPs will take advantage of spatial diversity, which is introduced by multi-path propagation. Especially, when the channel condition is not good enough, the benefits from spatial diversity will play a much more significant role. For instance, while the packet error rate is 0.3, the throughput is enhanced by 72% with two MRPs cooperative scheme. Even by one relay node scheme, the throughput is improved by 41%. As for the mechanism by three MRPs, we could observe that there is a cross between the curves of the proposed cooperative scheme and original scheme. This is because that with our scheme, spatial diversity is achieved at a cost of multiple transmission of the same packet. Only in the case that the PER is extremely low (almost error-free), the throughput of the original scheme could be a little higher than the proposed mechanism with three MRPs. Otherwise, the proposed cooperative mechanism outperform the original one when the PER increases. Furthermore, we could observe that as the channel condition deteriorates (PER higher than 0.34 in the figure), the more MRPs are provided, the higher throughput will be obtained. However, in the worst case where the PER is extremely high, almost zero throughput will be achieved for all schemes because all paths failed to deliver data.

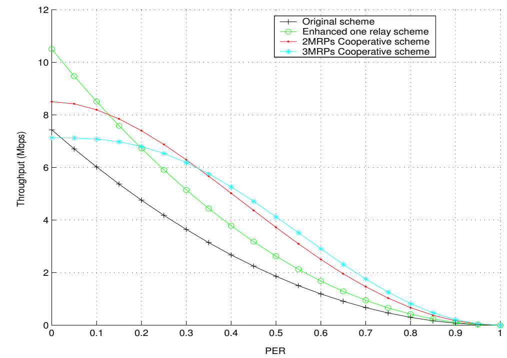

Fig. 4. Throughput performance comparison: Original vs Cooperative.

B. System Throughput as Packet Size Varies

As it is known, the packet size has a major effect on the efficiency of any MAC protocol. Fig. 5 studies this effect on the legacy 802.11 and the proposed MAC protocol in the case that the PER are 0.1 and 0.4, respectively. As expected, the saturation throughput for original MAC increases as the packet size grows. This is due to the fact that a lower percentage of channel time is occupied by the transmission of PHY and MAC overhead. We could also observe that when the packet size increases, the throughput of the proposed cooperative MAC protocols will increase more rapidly than the original 802.11 mechanism. On the one hand, this is due to the fact that in short length payload the transmission of the data frames is quite limited and thus the time for a node occupies the medium to transmit the frame is less significant for the performance of the network. In other words, it means there are enough bandwidth resources for transmission of the network traffic when the packet size is below a certain threshold. It could observe that this value is usually fairly small (e.g. approximately 110 bytes in the figure). However, above the threshold, the proposed MAC protocols will help mainly to boost the delivery of long packets. On the other hand, with multi-path transmission in our cooperative MAC mechanism, the probability of successfully obtaining a packet is much higher than that in the original 802.11. As the payload increases, more and more traffic requires to be transmitted. The cooperative MAC, by reducing the transmission time and increasing the transmission probability, increases the number of successfully transmitted data packets and thus increases the throughput. Consequently, the more payload in the network, the higher the cooperative throughput.

Additionally, we could also observe that compared with the case that PER is 0.1, in the case that PER is equal to 0.4 the slope of the curve with three MRPs is steeper than that of other curves. As a consequence the throughput will increase faster than that of the others. It means that when the channel condition deteriorates, more MRPs in cooperation would be beneficial.

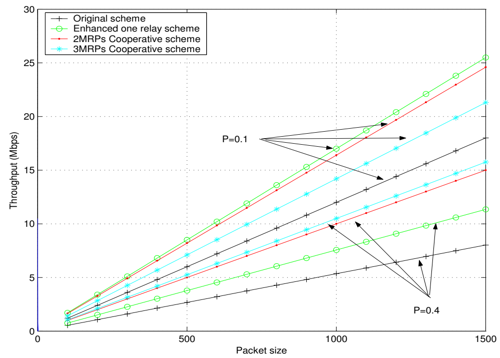

Fig. 5. Throughput comparison as the packet size increases.

C. Access Dealy Evaluation

Access delay is another performance metric critical for a wide variety of applications. One could imagine that the improvement in aggregate throughput also translates into better performance in the packet transmission delay. The access delay performance comparison between our cooperative MAC mechanism and the original DCF protocol is shown in Fig. 6. We could observe that the delays of our proposed MAC protocols are significantly lower than that of 802.11-based scheme. This is because that the novel MAC mechanism decreases the transmission time and thus more packets can be transmitted in a given period of time, leading to a fact that decreases the queueing and service time of the packets. Additionally, multi-path cooperative diversity guarantees that the probability of a successful transmission required by our proposed cooperative MAC mechanism is significantly higher than that in the original scheme. In other words, to meet the same performance requirement (packet delivery ratio) it should need more time to transmit the same packets if the original scheme is applied.

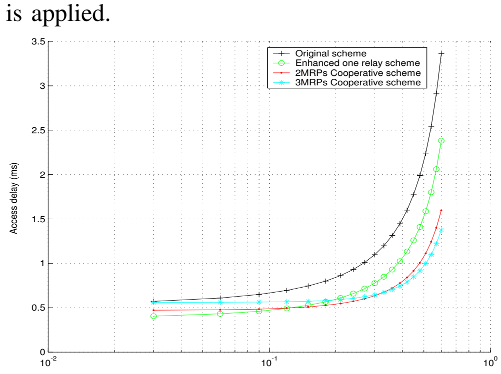

Fig. 6. Access delay performance comparison: Original vs Cooperative.

D. Further Discussions

In addition to the performance enhancement presented above, the proposed cooperative protocol has another great advantage, i.e. its potential to support more advanced signal processing techniques in the physical layer. For instance, Maximum Ratio Combining (MRC) filter could be used in diversity receivers [12]. In the cooperative access scheme, several copies of the data packet is received at the destination in the cooperative set. If there is a buffer at the destination to store packets, once it receives all the relayed packet, the copies of the data packet can be combined at the destination to obtain extra time diversity. Hence the throughput performance could be further improved.

VII. Conclusions

In this paper we have proposed a two-hop cooperative MAC mechanism for multi-hop wireless networks. The main contribution of this work that a two-hop cooperative MAC mechanism which deals with the case of no direct communication between the source and destination nodes has been proposed. The scheme takes full advantage of spatial diversity to improve system performance. The numerical results demonstrate that compared with the legacy non-cooperative scheme, significant throughput improvement and access delay reduction have been achieved by employing our proposed cooperative MAC protocol. In addition, the protocol introduces a distributed relay selection algorithm with collision avoidance so that it can be further extended to multi-hop wireless networks. As our future work, multiple cooperative MAC mechanisms in a large-scale network will be studied.

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