An Automatic Cooperative Retransmission MAC Protocol in Wireless Local Area Networks

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***Abstract*—Existing solutions for cooperation in wireless networks either require simultaneous transmission of source and relay nodes or impose major modifications to original MAC protocols. In this paper, a new efficient retransmission MAC protocol is proposed for IEEE 802.11 based cooperation communications, with minimum modifications to the DCF scheme. Throughput and access delay performance of the proposed protocols is analyzed in error-prone and highly temporally correlated channels. Numerical results show that significant benefits can be achieved with our cooperative protocol, compared with the legacy schemes.**

I. INTRODUCTION

Cooperative communications, which are proposed as a distributed approach to achieve spatial diversity in wireless environments, have recently become a hot research topic. In cooperative communications, the information is not only transmitted through a direct link from source to destination but the same data may also be forwarded by one or more relay nodes when necessary. In this way, system performance is enhanced in terms of network throughput, coverage, energy efficiency and so on.

The theory behind cooperation has been studied in depth and significant gains have been shown [1]$\sim$ [4]. Plenty of publications have designed various systems to implement cooperation, but most of them have not considered the constraints of legacy techniques in wireless networks. For instance, Code Division Multiple Access (CDMA) has been favored by many researchers [4]$\sim$ [6] to support simultaneous channel access in cooperative transmission schemes. However, many of today's mass-market applications based on IEEE 802.11, Zigbee etc. are using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for access control, in which simultaneous transmission of multiple stations is impossible, due to its low cost and relatively good performance.

We are particularly interested in MAC protocol design for cooperative communication in CSMA/CA based Wireless Local Area Networks (WLANs). In such context, existing cooperative CSMA/CA MAC design in the literature typically involves hardware assumptions at the physical layer. For instance, it is assumed that the radio hardware supports cooperative space-time coding for simultaneous transmissions in CD-MAC [7] [8]. Other literature about cooperative MAC design aims at solving the performance anomaly problem of the Distributed Coordination Function (DCF) scheme in the presence of multiple data rates. For example, a cooperative MAC protocol called CoopMAC [9] is proposed to achieve higher throughput in WLANs, in which high data rate stations always assist low data rate stations in their transmission by forwarding their traffic. Similar to [9], [10] is another example of MAC design which deals with the multi-rate issues in ad hoc networks. Persistent RCSMA [11] is claimed to be the first MAC designed to execute distributed cooperative automatic retransmission request scheme in wireless networks. In persistent RCSMA, all stations are invited to become active relays as long as they meet certain relay selection criteria. Then the relays will try to get access to the channel according to the DCF protocol. However, the introduced long defer time and random backoff time for each relay would decrease the throughput efficiency consequently. Besides, the work in [12] shows that it is sufficient to choose the best relay for one source destination pair to achieve full diversity in the presence of multiple relay nodes.

In this paper, we propose an opportunistic cooperative protocol, in which the cooperative (relayed) retransmission is initiated only if the direct transmission fails. Only one optimal relay is selected beforehand for a given source-destination pair. The automatic retransmission by the relay node tightly follows the direct transmission without any extra delay. Both a cooperative basic scheme and a cooperative Request-to-send (RTS)/Clear-to-send (CTS) scheme are proposed, with the latter one taking into consideration the existence of hidden terminals. The performance of the proposed cooperative MAC protocol is evaluated in error-prone and temporally correlated channels.

The rest of the paper is organized as follows. Brief background information on 802.11 DCF is given in Sec. II. After the system model is described in Sec. III, the proposed protocols are explained in details in Sec. IV. Throughput and access delay analysis is given in Sec. V, and the performance is evaluated compared with the original scheme in Sec. VI. Finally the paper is concluded in Sec. VII.

II. BACKGROUND INFORMATION ON 802.11 DCF

The DCF of IEEE 802.11 [13] is a "listen-before-talk" medium access scheme based on the CSMA/CA protocol. A transmitting station should listen to the channel for a Distributed InterFrame Space (DIFS) before it sends data packets. A random backoff scheme is also specified thereafter to avoid collisions. When the destination node receives the data frame successfully, it should return an acknowledgment (ACK) frame to the source node after a Short InterFrame Space (SIFS) interval. The above described two-way handshaking technique is referred to as the basic access scheme and illustrated in Fig. 1.

Fig. 1. IEEE 802.11 DCF basic access scheme.

To mitigate the effects of the hidden station problem, an additional four-way handshaking technique is defined, in which short RTS and CTS frames are exchanged before each data frame transmission, as shown in Fig. 2.

The RTS and CTS frames carry information about the length of the current frame exchange. This information can be read by any listening station, which is then able to update a Network Allocation Vector (NAV) field containing the time information during which the channel will remain busy. Therefore, when a station is hidden from either the transmitting or the receiving station, by detecting just one of the RTS/CTS frames it can suitably delay further transmission, and thus avoid collisions.

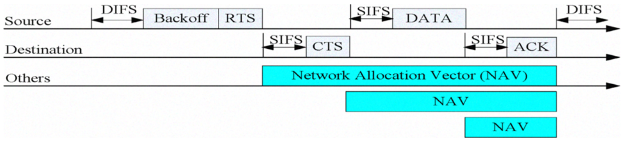

Fig. 2. IEEE 802.11 DCF RTS/CTS scheme.

III. System Model and Assumptions

The system model used to illustrate how our MAC protocol works is described in this section. As shown in Fig. 3, the model consists of a source station, S, a destination station, D, and a third node, R, which acts as a relay in the cooperation mode. The relay node is assumed to be pre-selected from a set of possible candidates.

In the system model, all the three nodes can hear each other. They are all working in the promiscuous mode, which means that a node will capture and process data packets it receives no matter whether they are addressed to it or not. Each packet transmission will start from S, with the intended receiver as D, but R will also receive and keep a copy of the sent packet. If the transmission from S to D fails, then R (instead of S) will automatically retransmit the original data packet to D.

We assume that the wireless channel between S and R is error-free, and the channels between S and D and between R and D are statistically independent of each other with identical bit error rate. Furthermore, two consecutive packets on the same channel are subject to temporally correlated channel fading and have the same state transition probability. The latter two assumptions have been validated in experiments carried out with 802.11*g* systems in typical office environments [14].

The experiments in [14] were set up with one sender and two receivers, which were placed close to each other, and the distance between the transmitter and the receivers was around 5 meters. The results have revealed two important observations: the channels exhibit strong time correlation for each receiver, while negligible correlation between the two receivers. Considering the reciprocal characteristic of the 802.11 wireless channels, the above observed results can be applied in our model with two transmitters and one receiver.

Moreover, a two-state Markov chain is built to model the channel with time correlation, as illustrated in Fig. 4. In this model, there are two states, ”1” and ”0”, representing that the packet has been received correctly or not, respectively. Let p_{ij} denote the transition probability from state i to state j, where i, j = 0,1. The following transition probabilities have been obtained from the experimental results: $p_{10} = 0.001$, $p_{11} = 0.999$, $p_{00} = 0.97$, and $p_{01} = 0.03$. These values indicate that the probability of another successful data packet transmission after a successful one on the same channel is as high as 0.999 and the probability of a successful transmission after an unsuccessful one is as low as 0.03, and so on.

In addition, the nodes in our model are assumed to be stationary, such as WLAN equipment in an office environment or mesh routers in a wireless mesh network. If the network works in ad hoc mode, the proposed system can be extended to a multi-hop scenario easily in which our three nodes act as a new virtual single hop along an end-to-end route.

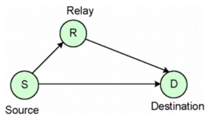

Fig. 3. System model.

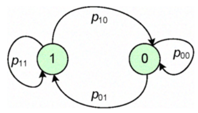

Fig. 4. Channel model by Markov chain.

IV. Cooperative MAC Protocols Design

Based on the system model presented in Sec. III, a new automatic cooperative retransmission MAC protocol is proposed for both the basic access scheme and the RTS/CTS scheme with maximal compatibility considerations with the 802.11 DCF protocols.

A. Cooperative Basic Scheme

The message sequences for the proposed cooperative basic access scheme are illustrated in Fig. 5. For a packet transmission, there are three cases that may occur: success in the direct transmission attempt from S to D(Case (a)); success in the cooperative transmission attempt from R to D(Case (b)); and transmission failure (Case (c)).

As the first step, node S sends out its data packet to D according to the original basic access scheme in 802.11. If the transmission succeeds, the message sequence will proceed exactly the same as the original scheme, as shown in Fig. 5 (a). Otherwise, R will automatically forward its received data packet to D after ACK timeout, without waiting for DIFS. For the purpose of protecting the ongoing cooperative retransmission sequences, a short control frame named Cooperative Allocation Vector (CAV) is piggybacked to the relay packet. As shown in Fig. 5 (b), if the cooperative transmission through R succeeds, an ACK will be relayed to S by R in order to guarantee a reliable transmission [1]. If even the cooperative retransmission fails, S has to wait for a longer ACK timeout

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[1] Since the direct transmission from S to D was not successful, it is likely that the ACK frame would also fail to reach S if it is sent directly to S on the same channel. Therefore, two step ACK is designed in our scheme.

which is 2*(SIFS+ T_{ACK}) to initiate the next transmission, as shown in Fig. 5 (c).

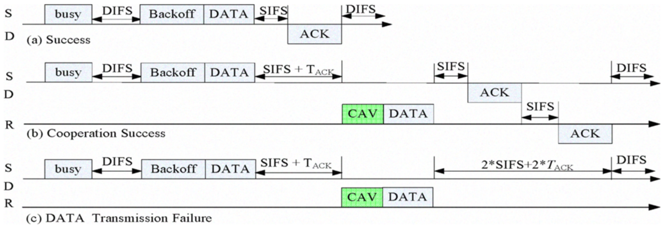

Fig. 5. Cooperative basic access scheme.

As mentioned above, a CAV packet is introduced in the cooperative basic scheme to reserve the channel for the following cooperative retransmission sequences. The CAV packet contains the length of the time duration from the beginning of the relay packet to the end of the second ACK packet, which can be used later by other nodes to set their NAV values. The CAV frame has the same frame format as RTS's, even though RTS is not used in the legacy basic access scheme. It is transmitted at a data rate from the basic date set in order to protect the whole transmission packet exchange over a larger area. In this way, all ongoing message sequences shown in Fig. 5 are well protected and can not be interrupted by other contending nodes in the transmission range.

B. Cooperative RTS/CTS scheme

The cooperation solution for the RTS/CTS scheme is illustrated in Fig. 6.

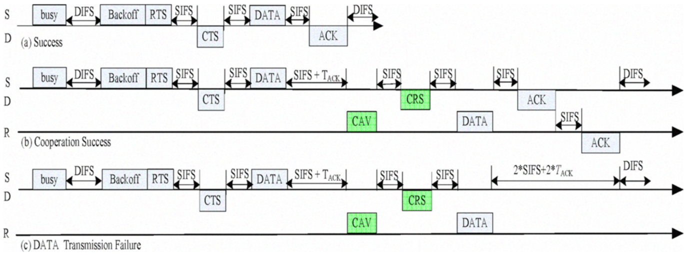

Fig. 6. Cooperative RTS/CTS scheme.

At the beginning of a transmission, S and D perform two handshakes the same as in the legacy RTS/CTS scheme. If the direct transmission fails, the relay node will start cooperative retransmission automatically as shown in Case (b) in Fig. 6. Besides CAV, another control frame named Clear for Relay to Send (CRS) is introduced in the cooperative RTS/CTS scheme to deal with the hidden terminal problem. The CAV and CRS frames carry the time duration information that will be consumed by their following cooperative retransmission sequences respectively to reserve the channel between R and D. They have basically the same format as RTS and CTS frames and will be transmitted at the same rate as the RTS and CTS frames respectively, in order to protect the cooperative transmission packet exchange in the sensing range. It might be considered to send another CRS from the source node to reserve the channel for the second ACK sent from the relay node. However, the assumption in our model implies that the relay node is generally close to the source node and their sensing ranges could overlap to a large extent. Hence the CRS frame from the source node is no longer necessary.

The rest of the protocol remains the same as the cooperative basic access scheme illustrated in the above subsection.

V. THROUGHPUT AND ACCESS DELAY ANALYSIS

The performance our cooperative protocol is analyzed in error-prone and temporally correlated environments respectively in the following two subsections.

A. Performance analysis in error-prone channels

In the 802.11 DCF scheme, the system time can be broken down into virtual time slots with each virtual slot being the time interval between two consecutive countdowns of backoff timers by non-transmitting stations [15]. The normalized system saturation throughput, denoted by S, is defined as the successfully transmitted payload bits per time unit. According to [15], S can be calculated as:

$$S = E[P]/E[T], \tag{1}$$

where $E[P]$ is the number of payload information bits successfully transmitted in a virtual time slot, and $E[T]$ is the expected length of the virtual time slot.

The access delay is defined as the delay between the time when a frame reaches the head of the MAC queue of the source and the time that the ACK frame is successfully received by the source's MAC. With the saturation throughput S, the average access delay of each frame is: (L is the average payload length):

$$D = L/S. \tag{2}$$

For calculating $E[P]$ and $E[T]$, the transmission probability in a virtual slot is needed. It can be expressed as follows [15]:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)}, \tag{3}$$

where p is the unsuccessful transmission probability conditioned on the occurrence of a transmission attempt in a given time slot. In the originally proposed Bianchi model, only collision is considered as a reason of unsuccessful transmission since the channel is assumed to be error-free. In this paper, the packet is transmitted successfully only if no collision happens and at the same time the packet is not corrupted during its transmission on the channel. Therefore, the probability p is rewritten as follows:

$$p = 1-(1-p_c)(1-p_e), \tag{4}$$

where p_c and $p_e$are the collision probability and the packet error probability of data packets when transmitted on the channel respectively. In Eq. (3), $W = CWmin$ denotes the minimum contention window size. The parameter m defines the relation $CWmax = 2^m CWmin$, where $CWmin$ and $CWmax$ are the sizes of the minimal and maximal contention windows, respectively.

Based on the above discussion, the $E[P]$ in the original scheme can be expressed as:

$$E[P] = p_{succ}L, \tag{5}$$

where p_{succ} is the probability of a successful transmission. Correspondingly, in our model,

$$p_{succ} = p_{tr}(1-p_c)(1-p_e), \tag{6}$$

where p_{tr} is the probability that there is one transmission from the source node in the considered slot time which equals to τ because only one node is transmitting in the model.

In the original scheme, $E[T]$ in Eq. (1) is calculated as:

$$E[T] = T_{idle}p_{idle} + T_{succ}p_{succ} + T_e(1-p_{succ}-p_{idle}), \tag{7}$$

where p_{idle} is the probability of an idle slot; T_{idle}, T_{succ} and T_e are the duration of a virtual time slot when it is idle, or there is a successful transmission or an unsuccessful transmission respectively.

In the original basic scheme, T_{succ} becomes

$$T_{succ} = T_e = T_{DATA} + T_{ACK} + SIFS + DIFS, \tag{8}$$

while in the original RTS/CTS scheme, we get

$$\begin{aligned} T_{succ} = T_e = T_{DATA} + T_{ACK} + T_{RTS} + T_{CTS} \\ +3*SIFS + DIFS. \end{aligned} \tag{9}$$

In the above equations, T_{DATA}, T_{ACK}, T_{RTS} and T_{CTS} represent the time used for transmitting the DATA, ACK, RTS and CTS frames respectively.

The saturation throughput S for the original schemes can be obtained by substituting Eq. (5) and Eq. (7) into Eq. (1), while the basic scheme and the RTS/CTS scheme are using different parameters in Eq. (8) and Eq. (9) respectively. Correspondingly, the access delay performance can be obtained by Eq. (2).

The performance for the proposed cooperative schemes can be analyzed in the same way. Now $E[P]$and $E[T]$ are rewritten as follows:

$$E[P]_c = (p_{succ} + p_{err1})L; \tag{10}$$

$$E[T]_c = T_{idle}p_{idle} + T_{succ}p_{succ} + T_{e1}p_{err1} + T_{e2}p_{err2}, \tag{11}$$

where p_{err1} is the probability of a transmission which fails on the direct channel and succeeds on the relay channel and p_{err2} is the probability of a transmission which still fails after the second retransmission attempt on the relay channel. As mentioned in Sec. III, the error probabilities on the original channel and relay channel are assumed to be identical to p_e. Therefore, p_{err1} and p_{err2} can be expressed as:

$$p_{err1} = p_{tr}p_e(1-p_e); \tag{12}$$

$$p_{err2} = p_{tr}p_e p_e. \tag{13}$$

In Eq. (11), T_{succ} ,T_{e1} and T_{e2} are the duration of a virtual time slot for Case (a), (b), (c), respectively. In the cooperative basic access scheme depicted in Fig. 5, they can be expressed as T^b_{succ} ,T^b_{e1} and T^b_{e2} as follows:

$$T^b_{succ} = T_{DATA} + T_{ACK} + SIFS + DIFS; \tag{14}$$

$$\begin{aligned} T^b_{e1} = T^b_{e2} = 2*T_{DATA} + 3*(T_{ACK} + SIFS) \\ +T_{CAV} + DIFS, \end{aligned} \tag{15}$$

where T_{CAV}represents the time used for transmitting CAV.

As for the cooperative RTS/CTS scheme depicted in Fig. 6, the duration of a virtual time slot for different cases is expressed as T^{RTS}_{succ}, T^{RTS}_{e1} and T^{RTS}_{e2} in the following:

$$\begin{aligned} T^{RTS}_{succ} = T_{DATA} + T_{ACK} + T_{RTS} + T_{CTS} \\ +SIFS + DIFS; \end{aligned} \tag{16}$$

$$\begin{aligned} T^{RTS}_{e1} = T^{RTS}_{e2} = T^{RTS}_{succ} + T_{CAV} + T_{CRS} \\ +T_{DATA} + 2*T_{ACK} + 4*SIFS, \end{aligned} \tag{17}$$

where T_{CRS} represents the time used for transmitting CRS.

Finally, the throughput of the cooperative basic scheme can be obtained from Eq. (1) through substituting Eq.s (12)~(15) into Eq. (10) and Eq. (11). For cooperative RTS/CTS scheme we will use Eq.s (16) (17) instead of Eq.s (14) (15). The access delay performance can be obtained correspondingly.

B. Performance analysis in temporally correlative channels

The throughput performance in the temporally correlative channel is analyzed based on the system model given in Sec. III. In our expressions, the retry limit for a single data packet is set to be 4 in all schemes. Applying Bayes' theorem, the average throughput for the original basic scheme is recalculated in the following, with the individual summands representing the different cases when 1, 2, 3 or 4 transmissions are needed.

$$\begin{aligned} S_2^{orig,b} = (1-p_e)\frac{L}{T_{s,1}} + p_e p_{01}\frac{L}{T_{s,2}} + p_e p_{00} p_{01}\frac{L}{T_{s,3}} \\ +p_e p_{00} p_{00} p_{01}\frac{L}{T_{s,4}}; \end{aligned} \tag{18}$$

In Eq. (18), p_e and L are the same as those in the preceding subsection and p_{00} andp_{01} are given in Sec. III. $T_{s,i}$, $(i = 1\ldots4)$, is the time duration consumed by data transmission which succeeds at the ith attempt. In the following expressions, $T_{b,j}$, $(j = 1\ldots4)$, is the average backoff time duration of the jth transmission, respectively.

$$T_{s,i} = \sum_{j=1}^{i} T_{b,j} + i*(T_{DATA} + T_{ACK} + SIFS + DIFS); \tag{19}$$

$$T_{b,j} = (2^{j-2}(CW_{min}+1) - \frac{1}{2})*T_{slot}. \tag{20}$$

Then the throughput of the cooperative schemes is recalculated in the following, with the individual summands representing the different cases of 1, 2, 3 or 4 transmissions needed:

$$\begin{aligned} S_2^{coop,b} = (1-p_e)\frac{L}{T_{b,1}+T^b_{succ}} + p_e(1-p_e)* \\ \frac{L}{T_{b,1}+T^b_{e1}} + p_e p_e p_{01}\frac{L}{T_{b,1}+T_{b,2}+T^b_{succ}+T^b_{e1}} \\ +p_e p_e p_{00} p_{01} * \frac{L}{T_{b,1}+T_{b,2}+2*T^b_{succ}}. \end{aligned} \tag{21}$$

The corresponding expressions for the RTS/CTS schemes can straightforwardly be obtained while the RTS/CTS and CAV/CRS frames are taken into consideration. Correspondingly, the access delay is calculated in the same way outlined in the above subsection.

VI. PERFORMANCE EVALUATION

We consider a pure 802.11*g* network for the evaluation of the novel cooperative protocols. The payload length is set to be 500 bytes. The sizes of RTS, CTS, CAV and CRS frames are set to be 20, 14, 20 and 14 bytes respectively. The length of the MPDU header is 24 bytes. The physical layer data rate of 802.11*g* is set to be 54 *Mbps* and the basic date rate for control packets is 6 *Mbps*. The size of the ACK packet is 14 bytes and it is transmitted at the same rate as the data packet, i.e. at 54 *Mbps*. The overhead of the physical layer header is 20 *us*. All the other default parameters in this section are configured according to the 802.11 standard.

A. Performance for error-prone channels

The saturation throughput based on the extended Bianchi model is shown in Fig. 7. It can be observed that the proposed cooperative MAC schemes generally outperform the corresponding original ones, and the improvement becomes larger at higher Packet Error Rates (*PERs*). For instance, when *PER* is 0.3, the throughput is enhanced by 10.1% when cooperative basic scheme is adopted and 11.1% when cooperative RTS/CTS scheme is adopted respectively, compared with the original schemes. This benefit comes from the reduction of DIFS and backoff time consumed in data retransmission of the original schemes. However, when PER is below 0.05, the performance of the proposed cooperative schemes is nearly the same with the original ones. This is because when the channel is in an ideal condition, few retransmissions are needed and the cooperative scheme works in the original noncooperative mode (Case (a) in Fig. 5 and Fig. 6), for almost all its packet transmissions. On the other hand, with poor channel conditions when *PER* is above 0.6, more significant relative throughput gains provided by the cooperative schemes could be observed if Fig. 7 is zoomed in, but the throughput is still inevitably low due to the heavy packet loss that is experienced for both the original and the cooperative schemes.

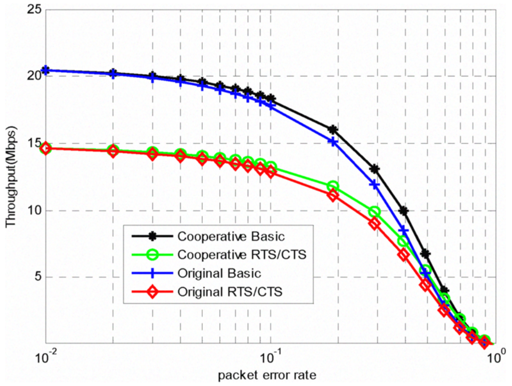

Fig. 7. Throughput performance: original vs cooperative.

The access delay performance is shown in Fig. 8. Obviously, the access delay is reduced significantly when cooperative retransmissions are introduced, especially in poor channel conditions. For example, when *PER* is 0.3, the access delay is reduced by 9.16% in the basic scheme and 8.82% in the RTS/CTS scheme when the proposed cooperative protocol is adopted. When *PER* is above 0.5, the access delay becomes unacceptably high for both schemes, even though the cooperative schemes are introducing greater improvements.

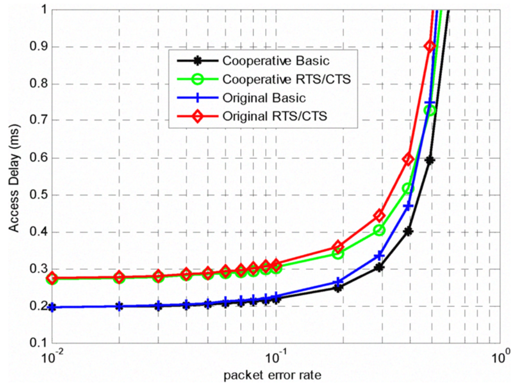

Fig. 8. Access delay: original vs cooperative.

In addition to the above results analysis, we can also observe that the RTS/CTS schemes always have inferior performance in the results in this study. This is because that there are no collisions according to our simplified system model. It indicates that the presence of the control frames such as RTS, CTS, CAV and CRS in the RTS/CTS schemes would only contribute negatively to extra overhead and decreases the performance without any positive effects in collision-free environments.

B. Performance in temporally correlative environments

According to the analysis in Part *B* of Sec. V, the throughput in temporally correlative channel is shown in Fig. 9 and the access delay performance is shown in Fig. 10.

In this case, more significant improvement of throughput by adopting the cooperative schemes is observed. For example, when *PER* is 0.3, the throughput is enhanced by 22.7% and 23.2% with the cooperative basic scheme and the cooperative RTS/CTS scheme respectively. More benefits are achieved compared with the gains in simple error-prone channels in Fig. 7. The reason is that the benefits not only come from the reduction of retransmission time in the novel cooperative schemes but also from the higher efficiency of spatial diversity exploited. In the highly temporally correlated model, time diversity, exploited by retransmitting data packets on the same channels according to original schemes, is not so evident any longer as it was in the time independent model. In contrast, in the proposed cooperative schemes, data packets are retransmitted on another channel, the relay channel, which is independent from the original one. In this way, spatial diversity introduced by multi-path propagations is exploited efficiently. In other words, the possibility that both packets transmitted over two independent channels fail would be much lower than the case when they are transmitted consecutively over the same channel in the temporally correlated model.

As shown in Fig. 10, the access delay performance is also significantly improved by the cooperative schemes. For instance, when *PER* is 0.5, the access delay is reduced by 22.2% and 22.6% in the basic scheme and the RTS/CTS scheme respectively when the cooperative protocol is adopted.

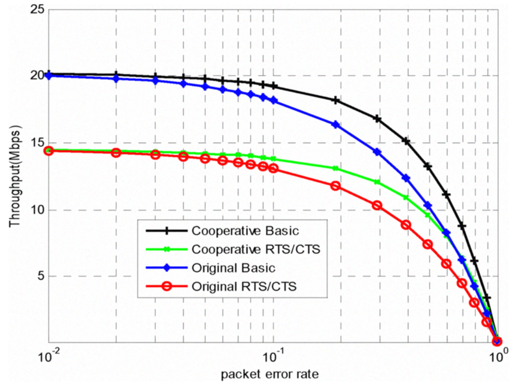

Fig. 9. Throughput performance in temporal coherent environments.

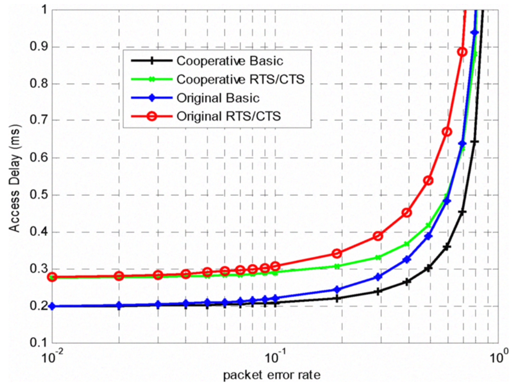

Fig. 10. Access delay in temporal coherent environments.

C. Further discussions

In addition to the performance enhancement presented above, the proposed cooperative protocol has great potential to support more advanced signal processing techniques. In the cooperative basic scheme, another copy of the data packet is received at the destination only after SIFS if the direct transmission fails. If there is a buffer at the destination to store the original packet, once the relayed packet is received, two copies of the data packet can be re-combined at the destination to obtain extra time diversity. Chase combing and incremental redundancy in Hybrid Automatic Repeat reQuest (HARQ) can be therefore potentially supported. Hence the throughput performance could be further improved.

In our model, the relay channel is assumed to have the identical bit error rate to the original channel between the source and the destination. However, in practice, the channel between the source and the relay is not necessarily error-free and the relay channel usually has a better channel condition. With appropriate relay selection schemes, we expect greater improvement from adopting the proposed cooperative schemes. For example, [16] has presented a new method to select the best available paths depending on the statistics of the wireless channels. Anyhow, relay selection itself is an interesting topic and is left for future work.

Furthermore, the system model used for performance evaluation is a simple one without other contending nodes during data transmission. Hence the advantage of the RTS/CTS scheme is not demonstrated in the results of this paper. The benefits and overhead of using the RTS/CTS and CAV/CRS frames would be further studied in more realistic environments in the presence of hidden terminals.

VII. CONCLUSIONS

Motivated by the idea of how to utilize the benefit of cooperative communications in WLANs with minimum modifications to the DCF protocol, we have proposed and studied an efficient automatic cooperative retransmission MAC protocol for both the basic access and the RTS/CTS schemes.

The numerical results have shown significant throughput improvement and access delay reduction achieved by our proposed cooperative protocols. For instance, when *PER* is 0.3, the throughput of the basic scheme is enhanced by 10.1% in the error-prone channel and 22.7% in the time correlative channel by the novel cooperative protocol. More gains are achieved in time correlative channels because spatial diversity, which is introduced by the independence between the original channel and the relay channel, is more efficient than limited time diversity achieved on the same channel.

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