An Adaptive Cooperative MAC Mechanism in Multi-hop Wireless Networks

Hongzhi Jiao, and Frank Y. Li
Dept. of Information and Communication Technology, University of Agder (UiA), N-4898 Grimstad, Norway
E-mail:{hongzhi.jiao, frank.li}@uia.no

Abstract—**In this paper, we propose a novel adaptive cooperative MAC mechanism that is specifically designed for two-hop cooperative communications where source and destination cannot hear each other directly. The proposed scheme employs an efficient adaptive relay selection algorithm such that the number of relay nodes is optimized for each cooperative transmission to maximize cooperation benefits and effectively avoid potential collisions with other transmissions. In order to determine the optimal number of relays we apply a training sequence in Hello message exchange, which provides us with a channel status indicator combining both bit-level and flow-level information. Numerical results show that compared with the original 802.11-based scheme and the static cooperative scheme, reliable transmission, reduced power consumption and significant throughput improvement have been achieved by using our two-hop adaptive cooperative MAC mechanism.**

I. Introduction

Cooperative communication has been recently proposed as a powerful means to improve network performance in wireless networks. Most existing work on cooperative communications focuses on investigating various issues at the physical layer [1]–[3] because it directly improves link reliability in which the advantages are often illustrated by analyzing signalling strategies based on information theory. For instance, many studies have paid attention to outage probability for different types of fading channels, while others exploit cooperative diversity by improving Bit Error Rate (BER), which could lead to reliable transmission and higher throughput.

However, in practice, cooperative gain may disappear if higher layer protocols are not properly designed. Thus, efficient cooperative communication should not only focus on PHY layer operation but also address the MAC layer protocol which is the bridge between the PHY layer and the higher layers.

In this paper, as an effort towards cooperative communication in multi-hop wireless networks we propose an Adaptive Cooperative MAC protocol (AC-MAC) specifically designed for two-hop communications. A salient distinction between this work and most existing cooperative MAC protocols [4]–[6] is that in our scenario the source node and the destination node cannot hear each other i.e., no direct communication between source and destination (a two-hop node from the source node) is possible.

To make our AC-MAC scheme work, a key element is relay selection. Although relay selection has been addressed by many publications [7], [8] as a means to improve reliability in wireless communication systems, they are not targeted at two-hop communications. The relay selection procedure in AC-MAC includes identifying a set of multiple relay nodes which are qualified to forward the received information toward the destination and a method to select the most appropriate relay(s) to forward information. In most of existing work each node monitors its neighborhood and determines a single node with best link quality as the relay node, solely based on link information of either the first hop or the second hop. In our work, however, we will dynamically select a set of nodes according to both links from source to relay and from relay to destination.

Meanwhile, the number of required relay nodes in our scheme are *adaptively* obtained according to two-hop combined channel conditions. As channel condition deteriorates, more relay nodes are needed to provide most potential spatial diversity gain. In order to measure time-varying channel condition, we employ a training sequence in Hello message exchanges, which is able to reflect channel variation in real time. As a consequence, the benefits of using our scheme are multi-fold: 1) increasing communication reliability over time varying channels; 2) increasing system throughput; and 3) reducing collision rate and transmission power.

The rest of the paper is organized as follows. The system model is described in Sec. II. After the proposed cooperative MAC protocol is introduced in Sec. III, the relay selection algorithm is presented in details in Sec. IV. Performance analysis is given in Sec. V, and the performance is evaluated and 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 upon which our cooperative protocol works in a two-hop manner. The system under consideration here is a static mesh network composing of multiple access points. Such networks are designed for high throughput and maximum reliability. As shown in Fig. 1, the system model consists of a source node, S, a destination node, D, and a number of intermediate relay nodes, i.e., R_1, R_2, $\cdots$, R_n, which may be used to forward data packets to destination node in cooperative mode. In our system model, relay nodes $R_i (1 \leq i \leq n)$ are the one-hop neighbors of both source node S and destination node D; D is the two hop neighbor of S; S cannot directly transmit data packets to D and vice versa. Each data packet transmission will start from S to D by packet forwarding via R_i.

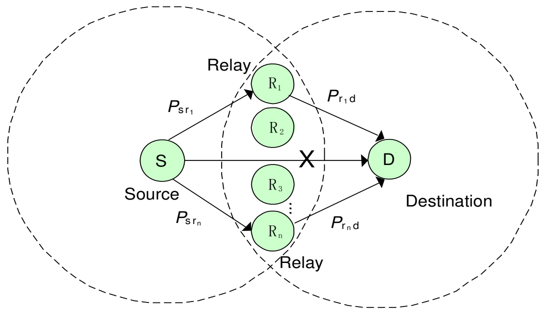

Fig. 1. System model for two-hop cooperative communication.

In the system model, the new MAC protocol adopts implicit ACK notification in order to reduce forwarding overhead. Implicit ACK is achieved by monitoring the packet forwarded from a relay node. For example in Fig 1, S confirms its transmission to R_1 as successful by overhearing R_1's transmission when a packet is forwarded to D. Furthermore, in our model, all channels are assumed to be statistically independent of each other.

III. Adaptive Cooperative MAC Mechanism Design

In our previous work [9], we have proposed a two-hop cooperative MAC mechanism by using two relay nodes in all circumstances. In this paper, we propose an enhancement to that protocol by adaptively employing an optimal number of relay nodes according to channel conditions. In brief, our AC-MAC has the ability to quickly switch among different number of cooperative relays, referred to as Multiple Relay Points (MRPs). The definition of MRP as well as how they are selected will be later presented in Sec. IV.

A. An Adaptive MRP Selection Scheme

The proposed AC MAC works as follows. S starts transmitting packets to one-hop relay nodes $R_i (i = 1, 2, ...n)$. Then a selected number of relays will forward the packet to D. As mentioned, this scheme is able to adaptively select an optimal number of relay nodes based on the collected channel condition. It works as follows: 1) obtain individual link quality; 2) calculate the overall two-hop combined link quality for all paths; 3) the source node decides how many MRPs will be used for the next transmission; 4) the protocol operates based on the number of determined relays; and 5) repeat the above steps for next packet transmission cycle.

Fig. 2 gives an example to illustrate how AC-MAC works when there are two MRPs. For each transmission cycle, the protocol works adaptively with more or fewer nodes.

B. The Cooperative Mechanism by MRPs

The proposed MAC mechanism can be flexibly applied to both one MRP and a larger number of MRPs. If there is only one MRP required, the MAC mechanism is designed similarly as the original 802.11 scheme operated in two-hops except that the back-off mechanism in the second hop is omitted. If more than one MRP is needed, the MAC mechanism will work in such a way as the message illustrated in Fig. 2.

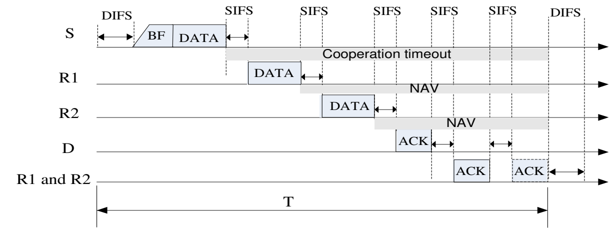

Fig. 2. Cooperative scheme by two MRPs.

As the first step, the MRPs are selected proactively by exchanging Hello messages. Through the Hello exchange process, a node is able to get information not only about its one-hop neighbors but also about its two-hop neighbors, so that each node in the cooperative system model is aware of the existence of each other. When node S has a packet to transmit, it senses the channel first. If the channel is idle for a DCF Inter Frame Space (DIFS) time and S has completed the required back-off procedure, the data packet will be sent. Due to the broadcast nature of wireless communication, all nodes around S will overhear the packets, no matter it is an MRP or not. However, only the MRP nodes will forward the successfully decoded data packets. Meanwhile, the Network Allocation Vector (NAV) inherited from the 802.11 standard will prevent possible collision taking place from other nodes rather than S, R_i and D, as described later.

Assuming that all 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 subsequently. Consider that MRPs may forward the packet at the same time, leading to packet collision in the wireless medium. To avoid collision, each MRP will obtain its transmission order from the source node by Hello message exchange. According to the combined link quality, the MRPs will start to forward the packet in a sequence, one after another. The MRP with highest combined link quality will have the smallest priority order as $k = 1$, where k indicates priority order, and relay the packet first. Then, the MRP with the second best channel condition will have the priority order as $k = 2$ and start forwarding after a specified time interval T_k. In other words, each MRP will start its own timer corresponding to the priority order to forward packets according to the following time schedule.

$$T_k = (k-1) * (\mathit{SIFS} + T_{DATA}), \tag{1}$$

where T_{DATA} represents the time used for transmitting DATA frame. Since all nodes are operating in a distributed and unsynchronized manner, each MRP needs to calculate its starting instant for forwarding the DATA frame. This is done by reading the Physical Layer Convergence Procedure (PLCP) header of the ongoing transmitting packet sent out by S, which contains the length of the being transmitted DATA frame.

When R_i is forwarding the DATA frame, S will receive the implicit ACK by overhearing data transmission to D, and decode the header of the packet to compare with the transmitted packet. If it was the same packet that S has just sent out, then S will know the MRP has received the packet correctly. Additionally, when the data packet is forwarded to D, the other nodes will keep back-off to avoid packet collision because they know the number of transmissions and these transmissions do not happen simultaneously.

After each relay which takes part in cooperation for this cycle of packet transmission has transmitted its packet, the reception phase at the destination node will be performed by decoding and sending an ACK to MRPs if the packet is successfully received. Upon receiving the ACK sent by D, the MRPs will forward the ACK to S. Due to the broadcast nature, D only needs to send an ACK and MRPs will overhear it respectively. The MRP with best channel condition will forward the ACK to S. Upon obtaining one ACK, S could initiate the next cycle of packet transmission. However, in case that S does not receive the ACK because of a transmission failure, the MRP with the second best path quality will send the ACK after $(T_{ACK} + \mathit{SIFS})$. Although the redundant ACK will bring overhead to the protocol, it is able to increase transmission reliability. Correspondingly, as long as S receives one ACK, the transmission cycle will be finished and S could initiate the next transmission. If S does not get any ACK during time interval $m \cdot (T_{ACK} + \mathit{SIFS})$ where m is the number of MRPs for this cycle, the retransmission has to be initiated.

C. Hidden Terminal Considerations

Depending on the locations of the involved nodes and channel conditions, some nodes may be able to hear the relay nodes, but not the source node. For instance, as shown in Fig. 3, N_1 is out of the carrier sensing range of S. When S sends its initial DATA frame to R_1 and R_2, N_1 may also send a packet at concurrent time, resulting in a collision at R_1. Similarly, a hidden node to MRPs but in the carrier sensing range of D can collide with the DATA frame transmitted by R_i.

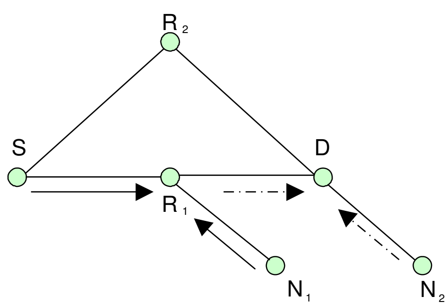

Fig. 3. Illustration of hidden terminal problems.

As mentioned earlier, a NAV field which is inherited from the IEEE 802.11 standard is introduced in the proposed scheme, by considering specially the duration of the whole cooperative transmission cycle. Briefly, the NAV field is included in all $m + 1$ copies of the DATA frame, starting from the initial DATA frame transmission by S, and the DATA frame forwarded by each MRP will specify different silent duration. This means that all nodes within the sensing range of S and MRPs will be informed that they have to wait for longer period before accessing the medium. As a specific NAV notification in the transmission cycle, the source node will reserve maximum time to ensure that its neighbors and other nodes which are hidden to source node and MRPs maintain silent during the whole cooperative transmission. We denote this period as *cooperation timeout* which starts after the initial DATA frame was sent out from S, as illustrated in Fig. 2. However, given the fact that two hops are involved in our scenario, collision is not completely eliminated since it may still occur during the first $T_{DATA} + SIFS$ duration after the source node's backoff interval.

IV. Relay Selection Algorithm

In this section we present a novel concept called multiple relay points which is used for relay selection. The scheme adaptively chooses an optimal number of relay nodes according to the hop-by-hop combined link quality, obtained through the enhanced Hello message.

A. Multiple Relay Point

In contrast to the concept of Multipoint Relay (MPR) in [10] in which a one-hop neighbor is selected to forward packets to as many as possible two-hop neighbors, we introduce a concept of *MRP in which one or more one-hop neighbors are selected as relays to forward packet to the same two-hop destination.* While the purpose of using MPR is to reduce overhead for routing message broadcast in ad hoc networks, the idea of introducing MRP is to achieve spatial diversity in multi-hop cooperative wireless networks through multi-path transmissions by MRP nodes. As illustrated in Fig. 1, this set may be composed of nodes R_1, R_2, ..., and R_n for the same destination D. However, only a portion of these candidates participate in packet forwarding, depending on channel conditions.

B. Optimal number of MRPs

With respect to the optimal number of MRPs, on the one hand, the smaller the set of multiple relay points, the more time-efficient the cooperation. On the other hand, the larger the set of multiple relay points, the more diversity gain. Consequently, there is a tradeoff between the number of MRPs and system performance.

For different channel conditions, there will be an optimal number of MRPs that maximizes system performance. In order to obtain the optimal number of MRPs, we adopt the same method as in [11]. It is verified that the best size of the cooperation group is around $\frac{1}{(1-P_{si})(1-P_{id})}$, where P_{si} is denoted as the probability of unsuccessful transmission between source and MRP candidates, approximatively taken as Packet Error Rate (PER), and P_{id} is taken as the PER for the relay channel between MRP candidates and destination. Since $\frac{1}{(1-P_{si})(1-P_{id})}$ is not a whole number in general, the optimal cooperation group size will be rounded to an integer.

Given the assumption in the system model that all channels are independent of each other, the received link quality is different for each path. If channel exhibits high quality, then fewer MRPs are required, and vice versus. Considering the fact that each MRP experiences different channel condition resulting in different number of required MRPs and a large number of relay nodes will decrease the transmission efficiency due to half-duplex transmission, we define the optimal number of the MRPs according the relay candidate which possesses the *best combined channel link quality* as

$$\textit{Optimal number of MRPs} = min\lceil \frac{1}{(1-P_{si})(1-P_{id})} \rceil. \quad (2)$$

Discussion. A case is studied through the PER equation in the presence of Additive White Gaussian Noise (AWGN).

$$\textit{BER}_n(\gamma) \approx a_n \cdot exp(-g_n \gamma), \quad (3)$$

where γ is the received SNR used to denote link quality, a_n and g_n are two parameters indicating channel quality and they are mode-dependent [12].

$$\textit{PER}(\gamma) = 1 - (1 - BER(\gamma))^L, \quad (4)$$

where L is the packet length. By substituting (3) into (4) we can observe that PER is a monotonicly decreasing function of SNR. The larger SNR, the smaller PER. As a consequence, the optimal number of MRPs relies on the MRP possesing the best link quality.

C. Neighbor Information Acquisition

Under the proposed scheme, each source node must detect the channel link condition to neighbor nodes in order to determine the best path for information relaying. The same as in [10], the one-hop and two-hop neighbor information as well as their link quality status are maintained by exchanging Hello messages between neighbors, in a proactive manner. The format of the Hello message is shown in Fig. 4.

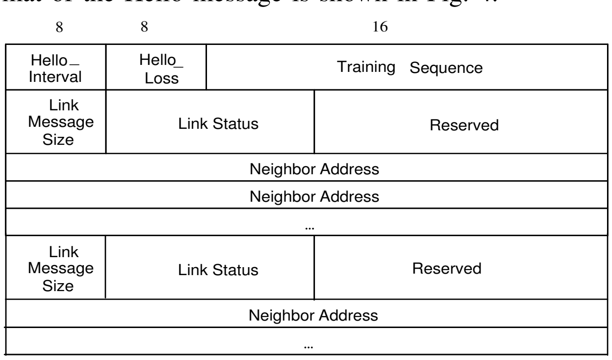

Fig. 4. The format of Hello messages.

Note that usually metrics that can be used to indicate link quality are distance, load, interference level, signal strength and Signal-to-Interference plus Noise Ratio (SINR) [5]. In many popular network protocols such as enhanced Optimized Link State Routing (OLSR) protocol, link quality is obtained in this way: Hello interval is specified as 2 seconds by default. In the period of 20 seconds with sliding window, the total received number of Hello messages divided by 10 will be the link quality in percentage. However, from the PHY layer point of view, due to the long latency of route updates and high control overhead, this measurement at the flow-level cannot quickly reflect channel dynamics and cannot achieve high bandwidth utilization. On the other hand from the higher layer point of view, the physical parameters in bit-level which are mapped to the network layer will finally be measured over a long time interval as input for routing decision. To combine these two perspectives we introduce an enhanced Hello message for channel condition estimation.

In our scheme, there is a 16 bits predefined training sequence [13] stored in the Hello message to measure channel condition. Because the channel is estimated in bit (symbol) level, it accommodates to all kinds of slow fading channels allocated between source and destination nodes. The result of performance verification indicates that this scheme improves the performance of the mechanism in multi-packet-level in terms of efficiency and latency compared with previous methods. The overhead incurred by this scheme could be expressed as: the average transmitted bits in the training sequence within specified time interval. The overhead is also affected by the number of neighbor nodes because the length of Hello message will be variable as the number of neighbors varies.

$$\textit{Overhead} = \frac{E[\textit{\# of bits transmitted}\ ]}{\textit{frame transmission interval}}. \quad (5)$$

The same as the source node, each relay candidate will obtain link quality between itself and the destination node. In other words, indirect 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. Consequently, the source node will acquire the link quality both from source to relay and from relay to destination. This channel information is used for MRPs selection.

D. Multiple Relay Points Selection

Cooperative MRPs are selected by the source node, which monitors its neighbors and dynamically maintains a table containing the information of MRPs. Since both hops are important for end-to-end performance, we should take the link quality of both hops into consideration. MRPs form an arbitrary subset of all the relay candidates which satisfies the following requirements: according to the criterion in the previous subsection m candidates from n relays are selected as MRPs which have the best combined link quality connecting from source to destination. h_i is the combined link quality balancing the two-hop links.

$$h_i = \frac{2}{\frac{1}{|a_{si}|^2} + \frac{1}{|a_{id}|^2}} = \frac{2|a_{si}|^2|a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2}, \quad (6)$$

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. Then it looks up the neighbor table and the neighbor R_i which maximized the function h_i is one with the *best* end-to-end path between the initial source and final destination.

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.

$$\eta = E[B]/E[T], \tag{7}$$

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

$$\mathit{E[B]} = P_{succ} * L, \tag{8}$$

where P_{succ} is the probability of a successful transmission and a function of per-hop packet failure probabilities. We express the throughput gain of AC-MAC as the ratio between the two-hop original DCF throughput η^{orig} and the cooperative throughput η^{coop}.

$$\alpha = \frac{\eta^{coop}}{\eta^{orig}} = \frac{P_{succ}^{coop} * E[T_{succ}^{orig}]}{P_{succ}^{orig} * E[T_{succ}^{coop}]}, \tag{9}$$

where P_{succ}^{orig} and P_{succ}^{coop} are the successful transmission probability of the original scheme and the cooperative scheme, perspectively, which can be denoted as follows.

$$P_{succ}^{orig} = (1 - P_{sr}) * (1 - P_{rd}), \tag{10}$$

$$P_{succ}^{coop} = 1 - \prod_{i=1}^{m} [1 - (1 - P_{si})(1 - P_{id})], \tag{11}$$

where P_{si} and P_{ri} are the PER of the first hop and second hop transmission, respectively.

$$\begin{aligned} E[T_{succ}^{orig}] = T_{hop1} + T_{hop2} = 2 * (T_{DATA} + T_{ACK} \\ + \mathit{DIFS} + \mathit{SIFS}) + E[T_{BF_1}] + E[T_{BF_2}], \end{aligned} \tag{12}$$

$$\begin{aligned} E[T_{succ}^{coop}] = (m+1) * T_{DATA} + 2 * T_{ACK} + \\ (m+2) * \mathit{SIFS} + \mathit{DIFS} + E[T_{BF}], \end{aligned} \tag{13}$$

where T_{BF_1} and T_{BF_2} are the back-off time duration of the transmission starting at the source and relay node in the two-hop DCF scheme by assuming that the node applies the binary exponential back-off scheme with the maximum back-off stage f (i.e., $CW_{max} = 2^f * CW_{min}$). T_{BF} is the only back-off time duration in the AC-MAC scheme.

VI. Performance Evaluation

To evaluate the performance of the proposed scheme, we compare the throughput performance of AC-MAC with that of 802.11 and the static cooperative scheme [9] in a two-hop transmission scenario. For comparison, we use a two-hop route with equal distance between each pair nodes. In every transmission, different number of potential relay nodes are generated to connect the source node and the destination node. The packet size is 512 bytes. The channel of any transmission pairs is modeled by Rayleigh fading. The configuration parameters are listed in Table I.

In our previous work [9], we have demonstrated that the static cooperative scheme outperforms the original IEEE DCF scheme. Fig. 5 shows the throughput gain of the proposed AC-MAC mechanism and the static scheme. If α is larger than 1, it means that the proposed scheme outperforms, and vice versa. It can be seen that the scheme with one-MPR and two-MRP always have higher two-hop throughput, which means that the cooperative MAC mechanism works more efficiently than the original DCF scheme. Especially, in low SNR regions, the three-MRP scheme exhibits higher throughput gain than the other schemes. It is because that with poor channel conditions more relays would fully take the advantage of spatial diversity, and efficiently increase the throughput from source to destination. However, when SNR becomes higher, the throughput gain will decrease, due to the delay and overhead incurred by multiple transmissions of the same packet. The protocol overhead will become too high when the three-MRP scheme is applied in high SNR regions. In such cases, the one-MRP scheme will perform best, as shown on the right-side hand of Fig. 5. As a consequence, by using the proposed AC-MAC, we could always take the advantage of the best envelop of the curves derived from static number of MRPs. In other words, we could always get maximum throughput gain under any channel condition.

TABLE I
Configuration parameters

Parameter	Value	Notes
Slot	9 μs	Slot time
SIFS	16 μs	SIFS time
DIFS	34 μs	DIFS time = SIFS + 2Slot
PLCP_Preamble	16 μs	PLCP preamble duration
PLCP_Sig	16 μs	PLCP signal field duration
DATA	500 bytes	DATA length
ACK	14 bytes	ACK length
MPDU	24 bytes	MPDU header length

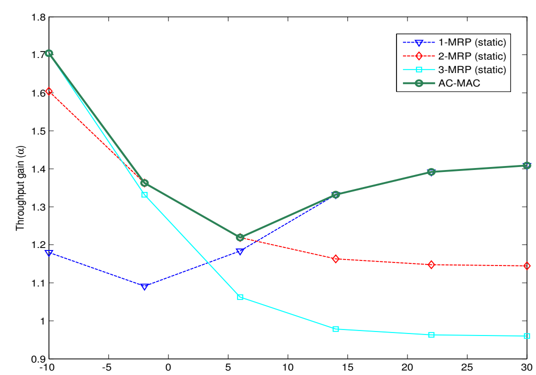

Fig. 5. Throughput gain of AC-MAC versus the static MRP scheme.

Fig. 6 illustrates the required average SNR versus throughput for the proposed AC-MAC mechanism, the two-MRP static scheme and the IEEE 802.11 scheme in two-hop transmission. As shown in the figure, in order to obtain the throughput of 6 Mbps, the scheme with two-MRP only require an average SNR around -5 dB, while the DCF scheme requires an SNR of 3 dB. However, with AC-MAC only -6 dB is needed to provide the same throughput. It means that with our scheme the transmission power can be greatly reduced to reach the same throughput performance. Furthermore, another advantage of the proposed scheme is that throughput could reach more than 10 Mbps, while the original DCF scheme could only obtain 7.4 Mbps.

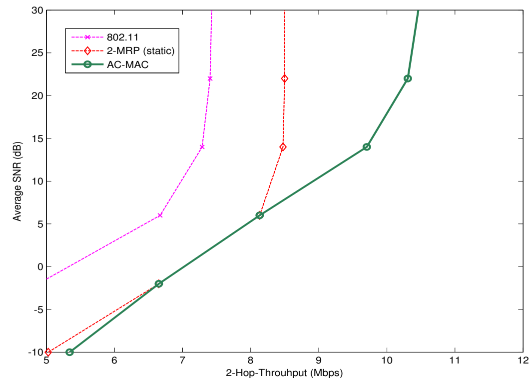

Fig. 6. Average SNR versus throughput.

In Fig. 7, we could observe that the proposed cooperative schemes outperform the original DCF mechanism with respect to the obtained two-hop system throughput by using directly PER as the X-axis. Firstly, the benefit comes from the reduction of transmission time in the novel cooperative MAC mechanism. Under the help of the same number of intermediate relay nodes, the cooperative scheme uses less time for a successful transmission cycle by using the implicit ACK method, as compared with the IEEE 802.11 scheme. Secondly, the large throughput gap between the IEEE 802.11 scheme and the two cooperative schemes is aslo due to packet collision, which is a main factor for system performance degration. The proposed AC-MAC mechanism could efficiently alleviate the hidden terminal problem, leading to packet collision reduction.

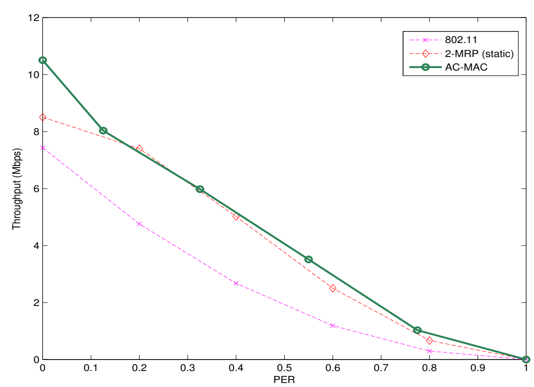

Fig. 7. Throughput performance comparison: original vs cooperative.

Again, the proposed AC-MAC mechanism has obtained higher throughput than not only the original DCF mechanism but also the static cooperative scheme could. The reason is due to the benefits derived from the spatial diversity exploited. In error-prone environments, the cooperative mechanism by multiple-MRP will take the advantage of spatial diversity, which is introduced by the 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 the two-MRP cooperative scheme, where two MRPs represent the optimal number of relays in this case.

However, if the optimal number of MRPs becomes too large, the throughput gain is not significant any more. In the worst case where the PER is extremely high, almost zero throughput is achieved for all schemes because all paths failed to deliver data. To summarize, our proposed adaptive cooperative scheme which selects an optimal number of MRPs according to the channel condition could always provide best system performance. This adaptive result is represented in Fig. 7 by the curve which is the envelop of the all curves for static numbers of MRPs.

VII. Conclusion

The main contribution of this work is a two-hop adaptive cooperative MAC mechanism which could adjust the optimum number of relay nodes required in error-prone environments. The scheme investigates the trade-off between the number of relay nodes and channel conditions to take full advantage of spatial diversity for performance improvement. The numerical results demonstrate that compared with the non-cooperative and static cooperative schemes, significant throughput improvement can be achieved by employing a proper number of MRPs. When the channel condition is very poor, however, further increasing the number of relays does not help.

References

[1] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part I: system description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[3] D. Chen and J. N. Laneman, "Modulation and demodulation for cooperative diversity in wireless systems," *IEEE Trans. Wireless Commun.*, vol. 5, no. 7, pp. 785–794, Jul. 2006.

[4] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs," *IEEE JSAC*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[5] S. Moh, C. Yu, S. Park, and H. Kim, "CD-MAC: Cooperative diversity MAC for robust communication in wireless ad hoc networks," *in Proc. of IEEE ICC*, Glasgow, UK, Jun. 2007.

[6] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Communications Magazine*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[7] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE JSAC*, vol. 24, no. 3, pp. 695–672, Mar. 2006.

[8] S. S. Ikki and M. H. Ahmed, "Performance of multiple-relay cooperative diversity systems with best relay selection over rayleigh fading channels," *EURASIP Journal on Advances in Signal Processing*, vol. 2008, no. 145, Jan. 2008.

[9] H. Jiao and F. Y. Li, "Cooperative medium access control in wireless networks: the two-hop case," *in Proc. of IEEE Wireless and Mobile Computing, Networking and Communications (WiMob)*, Marrakech, Morocco, Oct. 2009.

[10] T. Clausen and P. Jacquet, "Optimized link state routing protocol (OLSR)," *IETF RFC 3626*, Oct. 2003.

[11] L. Xiong, L. Libman, and G. Mao, "Optimal strategies for cooperative mac-layer retransmission in wireless networks," *in Proc. of IEEE WCNC*, Las Vegas, USA, Mar. 2008.

[12] K. J. Hole, H. Holm, and G. E. Øien, "Modulation and demodulation for cooperative diversity in wireless systems," *IEEE JSAC*, vol. 18, no. 7, pp. 1153–1158, Jul. 2000.

[13] P. Stoica and O. Besson, "Training sequence design for frequency offset and frequency-selective channel estimation," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1910–1917, Nov. 2003.