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RESEARCH ARTICLE

An efficient MAC protocol with cooperative retransmission in mobile *ad hoc* networks

Jeng-Long Chiang, Jang-Ping Sheu*, Huan-Chun Tseng and Wen-Tsuen Chen

Department of Computer Science, National Tsing Hua University, Hsinchu, Taiwan

ABSTRACT

In emerging wireless networks, cooperative retransmission is employed to replace packet retransmission between a pair of sender and receiver with poor channel condition. A cooperative MAC protocol which utilizes such benefit is proposed in this paper to improve the network performance in mobile *ad hoc* networks. In the proposed protocol, relay nodes between sender and receiver are used if the sender cannot communicate with the receiver reliably. Furthermore, the receiver may also stop forwarding the received data frame if the frame is received by the next-hop receiver on the route to the final destination node. Simulation results show that the proposed protocol outperforms previous works in terms of increased transmission reliability and reduced delay time. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS
cooperative networking, MAC protocols, mobile *ad hoc* networks

***Correspondence**
Jang-Ping Sheu, Department of Computer Science, National Tsing Hua University, Hsinchu, Taiwan.
E-mail: sheujp@cs.nthu.edu.tw

1. INTRODUCTION

Cooperative communication has received great research efforts in emerging wireless networks. Signal fading and interference are two major factors that impair system performance in mobile *ad hoc* networks (MANETs). In conventional wireless MAC protocols, nodes that are not the intended receiver will discard the overheard data frames; however, cooperation among these nodes is considered important in improving system performance [1].

Cooperative networking benefits from openness of the radio channel where nodes can help each other [2,3]. Cooperative retransmission schemes allow intermediate nodes between senders and receivers to relay the data frames. Researches on cooperative networking include information theoretical analysis of cooperative networking [3–6], routing methods (helpers selection) [7], and cooperative retransmission. Previous works show that the benefits of cooperative communications include (1) increasing communication reliability, (2) increasing transmission rate, and (3) reducing transmission power. SNR-based [4] and channel-gain-based [3,5,6] cooperative schemes exploit information and probabilistic theories to select suitable relay nodes in a node-to-node basis. Alternatively, the works in References [7–9] select relay nodes with considerations of the network-layer routes.

When the channel condition between the sender and the receiver becomes unreliable, it results into frequent retransmissions and thus decreases network throughput. The overhearing feature of wireless channels motivates our work to solve this problem by integrating emerging cooperative communication model. In this paper, a novel MAC protocol for cooperative retransmission is proposed. The goal is to improve both overall transmission reliability and data throughput.

Our major contribution is the MAC design that integrates cooperative MAC and routing mechanism. In the proposed protocol, relay nodes between the sender and the receiver are used when the sender cannot communicate with the receiver reliably. Two operations, namely route enhancement and route bypass, are introduced to enhance transmission reliability and efficiency, respectively. A relay node may be added into the route to improve the transmission reliability between the sender and the receiver. Furthermore, a receiver may stop forwarding the data frame if the data has been overheard by the next-hop receiver on the route toward the final destination. Simulation results show that the proposed protocol outperforms previous works in terms of increased transmission reliability and reduced delay time.

The rest of the paper is organized as follows. In Section 2, related works are briefly reviewed. The proposed MAC protocol, including both route enhancement and route bypass operations, is detailed in Section 3. Simulation results are shown in Section 4, followed by conclusions in Section 5.

2. RELATED WORKS

IEEE 802.11b [10] is a well-known standard for wireless local area networks (WLANs). The basic Medium Access Control (MAC) of IEEE 802.11b is distributed coordination function (DCF) based on CSMA/CA. Each wireless node has to sense the channel before data transmission. The Request-To-Send (RTS) and Clear-To-Send (CTS) control frames are employed to avoid collisions as well as the hidden terminal problem by setting the Network Allocation Vector (NAV). A data frame can be sent only when the channel is sensed idle, and finally an acknowledgment frame (ACK) will be sent by the receiver when the data frame is received without errors.

The existing cooperative retransmission MAC protocols can be classified into reactive [11,12] and proactive cooperative schemes [4,13–15]. In the reactive cooperative schemes [11,12], relay nodes will launch retransmission process only when the ACK for a transmitted data frame is missed. In the proactive cooperative schemes, differently, cooperative relay nodes are prearranged to relay data frames according to random selection [4,13,14] or the SNR (Signal-to-Noise Ratio) between nodes [15].

In Reference [11], a MAC protocol designated for multiple relays operating on orthogonal time slots is proposed based on hybrid-automatic repeat request (ARQ). The missed data frame can be retransmitted by the relay nodes which have overheard the data frame instead of the sender. In Reference [12], the authors proposed a cooperative ARQ scheme for mobile *ad hoc* networks where wireless channels have highly correlated frame-error profile. In Reference [13], rDCF, a novel MAC-layer relay-enabled distributed coordination function (DCF) protocol, was proposed to exploit the multi-rate capability in physical-layer. The rDCF nodes relay packets to each receiver in different rates according to their channel conditions.

As mentioned, relay node selection can be based on the channel conditions among senders, relay nodes, and receivers. In Reference [4], a relay node is chosen according to the SNRs between itself and the sender, and itself and the receiver. The better the SNRs is, the shorter the back-off time to access the channel. A cross-layer cooperative MAC protocol [15] employed a similar concept, but the back-off timer is replaced with busy tones for distributed relay selection scheme. In addition, adaptive modulation and coding and multimode transmission are scheduled together to improve the network throughput.

CoopMAC, which is based on the existing IEEE 802.11b DCF mode, was proposed in Reference [14]. An helper (i.e., relay node) can be selected by the sender to relay the data frame if the new path, the sender, the helper, and the receiver, is better than the direct link between the sender and the receiver. Nodes that are capable of being the helpers for the

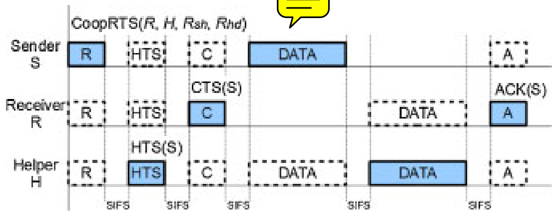

Fig. 1. ~~A cooperative retransmission scheme for CoopMAC protocol.~~

sender must satisfy the following inequality:

$$\frac{1}{R_{sh}} + \frac{1}{R_{hd}} > \frac{1}{R_{sd}}$$

here R_{sd} is the rate of direct transmission between the sender and the reciever, R_{sh} is the rate between the source and the helper, and R_{hd} is the rate between the helper and the receiver. These rates can be obtained through monitoring normal message exchanges.

The typical process of data transmission in CoopMAC is shown in Figure 1. When cooperative data transmission is launched, the sender selects one of the potential helpers in its CoopTable, and the selected helper will be specified in the CoopRTS. If the helper can relay the data frame at specified data rates, it will reply an HTS (helper ready to send); otherwise, the helper does nothing.

As shown in Figure 1, the sender receives both the HTS from the helper and the CTS from the receiver. It then sends the data frame to the helper, which will relay the data frame to the receiver. Finally, the receiver sends a ACK back to the source to completes the data transmission. If no ACK frame is received by the source station after timeout, the source station would follow the legacy 802.11 retransmission procedures.

3. THE PROPOSED PROTOCOL

In our protocol, if the receiver cannot receive the data frames sent from the sender, a suitable relay node between the sender and the receiver would help on retransmitting the data frame. In addition, if the two-hop receiver (the next-hop node of the receiver) can receive the data frames sent from either the sender or the relay node, the receiver does not forward the data frames to the next-hop node again.

The information of two-hop nodes has to be learned by each node from the routing mechanism. As in IEEE 802.11b, data frames are sent after RTS/CTS exchanges. The RTS used in our protocol is modified to include the sender *id*, receiver *id*, and the next-hop receiver *id* and is denoted as RTS (sender *id*, receiver *id*, two-hop receiver *id*). The above information is also included in each of subsequent data frames and they are denoted as DATA (sender *id*, receiver *id*, two-hop receiver *id*).

The nodes in the overlapped communication range of both sender and receiver can become relay nodes. For the example in Figure 2, nodes *B* and *C* are covered by the com-

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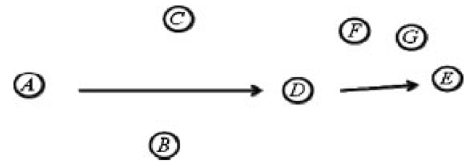

Fig. 2. Nodes *B* and *C* can serve as relay nodes on the link *A* to *D*, while nodes *F* and *G* can serve as relay nodes on the link *D* to *E*.

munication ranges of both nodes *A* and *D*. When sender *A* sends data frames to receiver *D*, both *B* and *C* can overhear the transmissions and thus can be potential relay nodes of sender *A*. In this case, sender *A* sends a RTS (*A*, *D*, *E*) to receiver *D*. Upon receiving a corresponding CTS from *D*, *A* then sends a data frame DATA (*A*, *D*, *E*) to *D*. Finally, *D* sends an ACK frame back to *A* for correct reception the data frame. Figure 3 illustrates this normal case where cooperative retransmission is not used.

If receiver *D* does not correctly receive the data frame, cooperative retransmission then takes place. This can be detected because the receiver will not reply an ACK. The potential relay nodes (i.e., node *B* and node *C*) then contend for relaying the data frame. Our protocol differs from CoopMAC in that a relay node is not determined by sender; on the other hand, a relay node is determined through contention in a distributed manner.

To implement our cooperative retransmission scheme, two new types of acknowledgment frames, called H1-ACK and H1-CONF, are introduced. When a relay node wins the contention, it sends an H1-ACK to access the channel. Contention resolution can be based on the SNRs of the relay node to both the sender and the receiver as proposed in Reference [4].

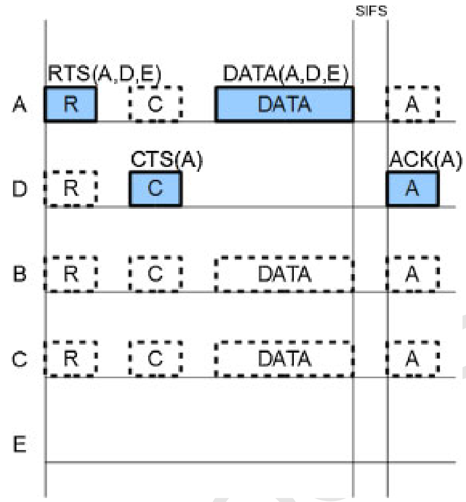

Fig. 3. The handshake of our protocol without cooperative retransmission.

In our protocol, we set the backoff time in slot unit, and four slots are used for the contention resolution among potential relay nodes. Each potential relay node selects one among the four backoff slots based on its SNRs to the receiver. The better the SNR is, the earlier the backoff slot is chosen, and thus the shorter the back-off time the relay node waits to access the channel. Figure 4 shows the case that relay node *B* wins the cooperative retransmission and it replies with an H1-ACK, followed by the data frame.

Once cooperative retransmission takes place, it implies that the channel between the sender and the receiver may be unreliable. The ACK replied by the receiver after receiving the retransmitted data frame may also lose due to the unreliable channel. In CoopMAC scheme, the sender will launch standard IEEE 802.11b data retransmission, and hence a

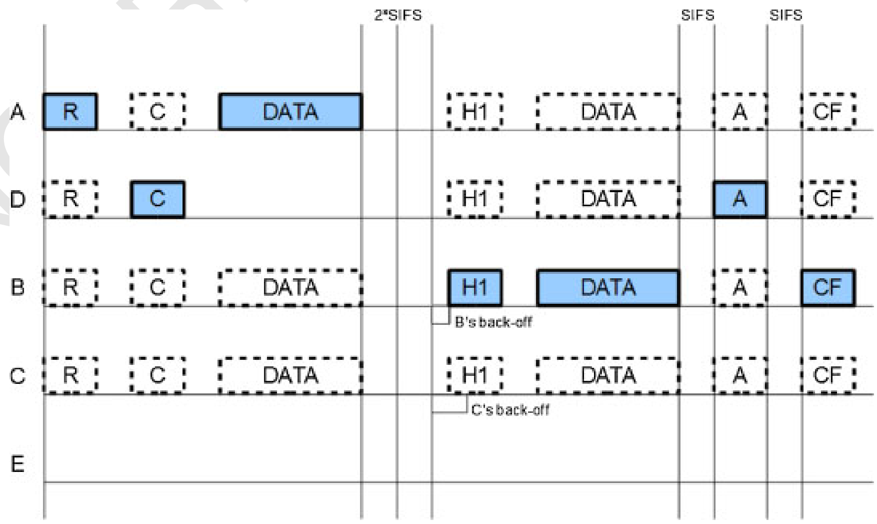

Fig. 4. The receiver losses the DATA but overhears by relay nodes. Then the relay nodes send H1-ACK to contend the channel and the winner sends DATA frame to receiver.

duplicate data frame will be retransmitted. In our protocol, however, the relay node which retransmitted the data frame will send an H1-CONF (denoted as CF in Figure 4) after hearing the ACK from the receiver. This allows the sender to be notified that the receiver has successfully received the data frame and avoids duplicated data frames be retransmitted. Notice that only the ACK for retransmitted data frame, rather than that in the direct transmission, is protected by H1-CONF.

In addition to the base cooperative retransmission scheme, we also introduce two operations to enhance transmission reliability and efficiency. The first is route enhancement while the other is route bypass. Both operations can be regarded as a cross-layer design. The route enhancement operations add relay nodes in the original route from the ultimate source station toward the ultimate destination station. The route bypass operations allow alleviating duplicate data transmission and the third new type of acknowledgment, namely H2-ACK, is used in route bypass.

3.1. ~~Add relay node to route~~

In order to maintain transmission reliability, the sender will add a relay node to its routing table upon receiving k times of H1-ACK from the same relay node. This indicates that the receiver has failed data reception for k times, and the same relay node has helped data retransmission for k times. This implies that the route through the relay node is more reliable than the original link. In our protocol, we suggest ~~that the sender replaces the receiver with the relay node to be its immediate next hop toward the ultimate destination node.~~ In other words, the route enhancement operation updates the new route to become the sender, relay node and then the receiver.

In our work, we found that setting k as two (in this case the relay has shown enough stable connectivity to both sender and receiver) can improve transmission reliability while preventing node ping-pong effect when $k = 1$. That is, if a relay node has successfully retransmitted two consecutive data frames for the same pair of sender and receiver, the sender will add this relay node as its next hop in the routing layer for the purpose of maintaining transmission reliability. The setting of k is further studied in Section 4.

3.2. Route bypass

In an MANET, the communication channels between nodes are influenced by both environments and node mobility. It is possible that the sender can directly communicate to its two-hop receiver. We also suggest the route bypass operation in our protocol in order to alleviate duplicate data transmissions and reduce the routing hops between the source and destination. The proposed route bypass operation allows immediate receiver not to forward the same data frame to its next-hop receiver if the data frame has been overheard by the next-hop receiver.

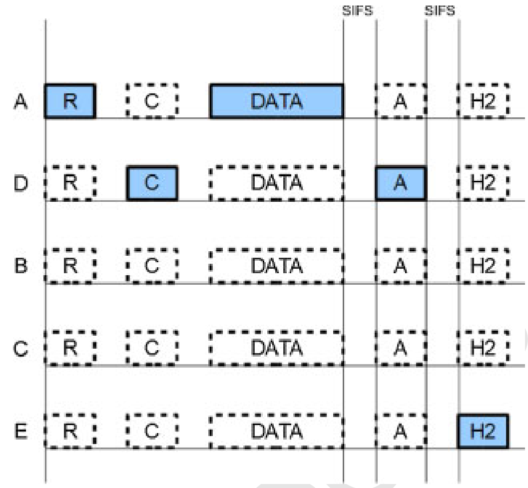

Fig. 5. The two-hop receiver *E* directly hears the data frame from sender *A* and then ~~response~~ with ~~an~~ H2-ACK.

When both the RTS and the data frame can be received by two-hop receiver of the sender, the two-hop receiver will acknowledge with an H2-ACK. The H2-ACK is sent following the ACK sent by the receiver after one SIFS and it notifies the receiver that the two-hop receiver has also received the data frame. Therefore, the receiver can cease forwarding the data frame again to this two-hop receiver.

There are two advantages of route bypass in our protocol. Firstly, the one-hop receiver of the sender does not have to retransmit the data frame to its next-hop receiver when the next-hop receiver has received the data frame directly from the sender. Secondly, if the sender can also receive the H2-ACK frame, the sender can update its routing table to directly communicate to this two-hop receiver in subsequent data transmissions.

Again, we use the original route $A \to D \to E$ in Figure 2 to illustrate our route bypass operations. Figure 5 shows that if sender A can receive an H2-ACK sent from the two hop receiver E following the ACK from receiver D, it indicates that E has also successfully received both RTS (A, D, E) and DATA (A, D, E). In this case, the route can be updated to $A \to E$ to reduce transmission cost and improve ~~the~~ routing performance. Similar to the process of adding relay node to new route, route bypass only takes over after the sender receives two consecutive H2-ACKs to avoid potential ping-pong effect of instantaneous good state of the transmission channel.

The route bypass operation also works in the case of cooperative retransmission. When the two-hop receiver correctly receives the data frame that is retransmitted by the relay node, it will also reply an H2-ACK so as to prevent the receiver from forwarding the same data frame. Notice that in the case of cooperative retransmission, the H2-ACK is delayed one SIFS following the H1-CONF sent by the relay node. The frame interaction is illustrated in Figure 6.

Finally, if the relay node has received two consecutive H2-ACKs from the two-hop receiver, it can also bypass

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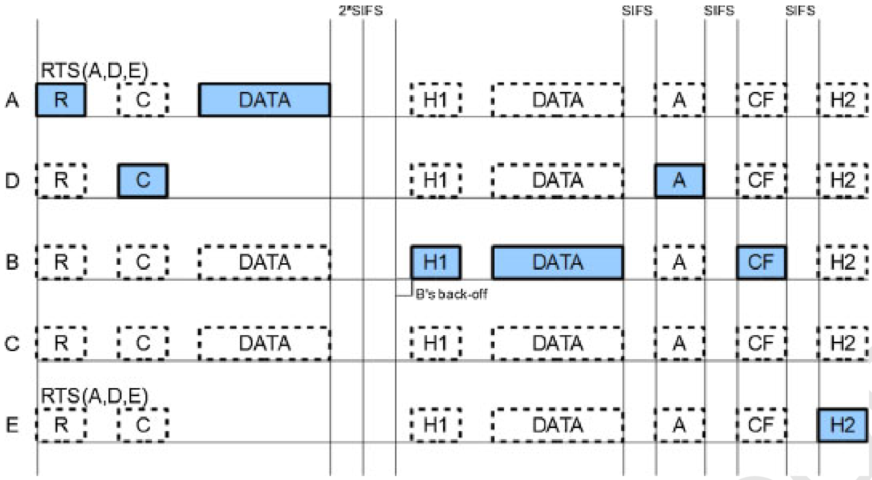

Fig. 6. The two-hop receiver *E* can hear the data frame from relay node *B*. After receiving the ACK from *D* and the CF from *B*, the two-hop receiver *E* sends ~~an~~ H2-ACK to the relay node *B*.

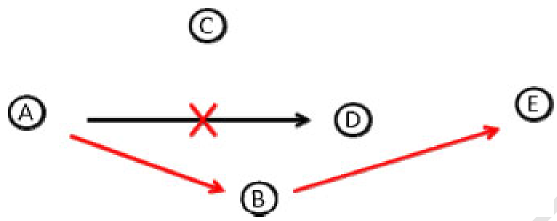

Fig. 7. The new path becomes sender *A*, relay node *B*, and then two-hop receiver *E* after route enhancement and route bypass operations.

the original receiver. In an extreme case as shown in Figure 7, where both route enhancement and route bypass occur simultaneously among sender *A*, relay node *B*, and the two-hop receiver *E*, the new route becomes $A \rightarrow B \rightarrow E$.

3.3. Protocol summary

We elaborate our main protocol in the following paragraphs from the view of sender, receiver, and relay node, respectively. For a sender, when a data frame is to be delivered, it sends the data frame after an RTS/CTS exchange. The detailed description is provided as follows:

(1) If the sender receives an ACK sent by the receiver, it means that the receiver has correctly received the data frame and the transmission completes. The sender then waits to see whether an H2-ACK is received. If two consecutive H2-ACKs from the same two-hop receiver have been received, the sender performs the route bypass operation as mentioned in Subsection 3.2.

(2) If there is no ACK received after one SIFS following the data frame, the sender then waits for an H1-ACK. If an H1-ACK is received, the sender learns that previous transmission has failed and a relay node will perform a cooperative retransmission. It then waits for either the ACK or the H1-CONF which indicates that the cooperative retransmission has succeeded, and the transmission completes. On the other hand, if neither the ACK nor the H1-CONF is heard, it means that the cooperative retransmission also fails and the sender will follow standard IEEE 802.11b data retransmission. During this process, if two consecutive H1-ACKs from the same relay node have been received, the sender performs the route enhancement operation as mentioned in Subsection 3.1.

(3) If neither the ACK nor an H1-ACK is heard, the sender learns that the transmission has failed and there is no relay node to perform cooperative retransmission. The sender will perform the standard IEEE 802.11b sender retransmissions.

The detailed description for the receiver after a successful RTS/CTS exchange is provided as follows:

(1) If the data frame is successfully received, the receiver replies an ACK to complete the transmission. It then waits to see whether an H2-ACK is received. If an H2-ACK is received, the receiver will stop forwarding the data frame to the next-hop receiver. Otherwise, the transmission will continue toward the end destination.

(2) If the data frame sent by the sender is not received, the receiver then waits to see if there is an H1-ACK. If an H1-ACK is sent by a relay node, the receiver learns that the data frame will be retransmitted by the relay node. If this retransmitted data frame is correctly received, the receiver then sends an ACK to the sender, which will be followed by an H1-CONF sent by the relay node. It then waits to see whether an

H2-ACK is received and proceeds as in case 1. On the other hand, if the cooperative retransmission also fails, standard IEEE 802.11b sender retransmission will take over.

(3) If neither the data frame nor an H1-ACK is received, it means that there is no relay node can help on retransmitting the data frame, the receiver will wait for the standard IEEE 802.11b sender retransmission.

For a relay node, it overhears the ongoing data transmissions between the sender and the receiver after hearing the RTS/CTS exchange. The detailed description is provided as follows:

(1) If an ACK is sent by the receiver after the data frame, the relay node do nothing and the transmission completes.
(2) If there is no ACK heard during two SIFSs following the data frame, the relay node computes a back-off timer based on its SNR to the receiver and waits for any H1-ACK sent by other potential relay nodes. If an H1-ACK is heard before its back-off timer expires, the relay node does nothing.
(3) If there is no other H1-ACK heard, the relay node will send an H1-ACK on timer expiration. It then retransmits the data frame and waits for an ACK from the receiver. If the ACK is received, the relay node then sends an H1-CONF following the ACK. The reply node then waits to see whether an H2-ACK is heard. If two consecutive H2-ACKs from the same two-hop receiver have been received, the relay node then performs the route bypass operation as mentioned in Subsection 3.2.
(4) Finally, if there is no ACK received after the relay node retransmits the data frame, it means that the cooperative retransmission also fails. In this case, the relay node does nothing and the standard IEEE 802.11b sender retransmission will take over.

4. PERFORMANCE EVALUATION

The performance of our protocol is evaluated through simulations with the Network Simulator version 2 (NS2) [16]. We compared the performance of our protocol with those of both 802.11 DCF and CoopMAC. The set of main parameters used in the simulations follow the default values specified in IEEE 802.11b standard as shown in Table I. In our simulations, we use TwoRayGround as radio propagation model and[Q2] dynamic source routing (DSR) [17] as network-layer routing protocol. The DSR is modified to obtain the information of two-hop receivers and enable route enhancement and route bypass operations. Finally, we use Random Walk Model [18] for node mobility.

In our simulations, three scenarios with 200, 300, and 400 mobile nodes are placed randomly in a 500 m × 500 m area. The transmission range of each node is 100 m and the speed of each node is between uniformly 0–10 m/s. Five-

Table I. Parameters used in simulations.

MAC header	272 bits
RTS	352 bits
CTS	304 bits
ACK	304 bits
H1-ACK, H2-ACK	304 bits
SIFS	10 μsec
DIFS	50 μsec
Slot time	20 μsec
aCWMin	31 slots
aCWMax	1023 slots

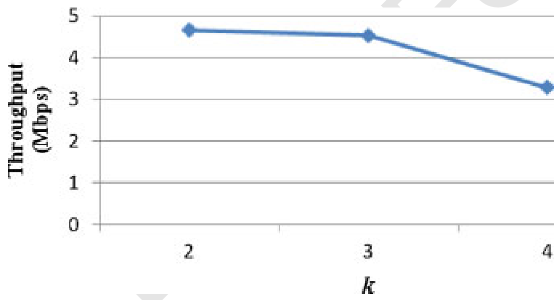

Fig. 8. ~~Throughput~~ with different values of *k*.

hundred data frames, each of size 512-Byte, are sent from each random pair of senders and receivers within 10 s. For each scenario, we compare the frame retransmission rate, hop count, and throughput.

As mentioned in Section 3.1, a relay node which consecutively helps retransmitting the data frame can be added into the sender's routing table to enhance the transmission reliability. This is triggered by the sender after hearing *k* H1-ACKs. We conducted a simulation to determine a reasonable value of *k*, and the result is shown in Figure 8. In our simulations, we found that setting *k* as 2 (in this case the relay showed enough stable connectivity to both sender and receiver) showed the best throughput due to improved transmission reliability. We also found that setting *k* larger than 2 will decrease the overall throughput as shown in Figure 8 due to less occurrences of adding relay node to route, which help on both high transmission rates and reliability between nodes.

With the above settings, we first compare the frame retransmission rates of IEEE 802.11b, CoopMAC, and our protocol. As shown in Figure 9, the performance is degrading in the order of 802.11b, CoopMAC, and our protocol. While the frame retransmission rate is about 20–25% in 802.11b DCF, that in CoopMAC reduces to about 10% Q2 because there are some relay nodes to help retransmitting data frames. Our protocol performs the best among the three and the retransmission rate of our protocol is about 7%. The reason is that some relay nodes are actively added to the route to reduce unreliable data transmissions between original senders and receivers. Furthermore, less retransmission rate also implies less packet loss rate since data retransmissions are caused by packet losses.

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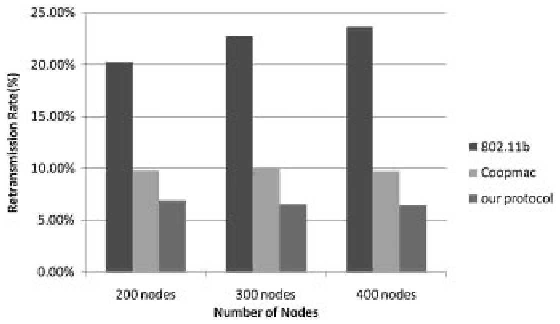

Fig. 9. Frame retransmission rates ~~of three protocols~~ with different number of nodes.

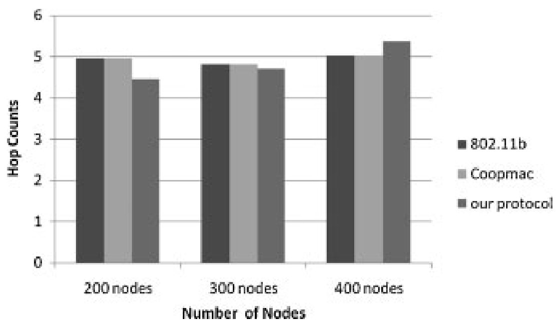

Fig. 10. ~~Number of~~ hop counts with different number of nodes.

In Figure 10, we show the number of hop counts of the three protocols. Since the 802.11b DCF and CoopMAC protocols cannot dynamically change their routing paths, they have the same performance of hop counts in the routing layer. However, our protocol can dynamically insert or remove the forwarding nodes according to the current channel conditions and thus shows less hop counts in some scenarios. Our protocol has less number of hop counts than the other two protocols in the cases of 200 and 300 nodes. However, in the case of 400 nodes the hop counts of our protocol are a little higher than 802.11b DCF and CoopMAC. The reason for that is there are more collisions occurred in the dense environment so there are more relay node be added into the route. In this case, however, the frames retransmission rate is reduced and the network throughput is improved (Figure 11) even through the number of hop counts is slightly increased.

In Figure 11, the data rates of 802.11b DCF, CoopMAC, and our protocol for 200 nodes are 2.8 Mbps, 4.2 Mbps, and 4.6 Mbps, respectively. The throughput of the three protocols increases as the number of nodes increases. Our protocol outperforms both 802.11b DCF and CoopMAC because both unreliable and slow links are replaced by adding reliable nodes between senders and receivers. In other words, the ability of changing routing path allows our protocol to adapt to the communication environments. Besides, we can also reduce the number of frames forwarded in the entire network if the two-hop receiver can directly receive the data frames sent from the sender or the relay node.

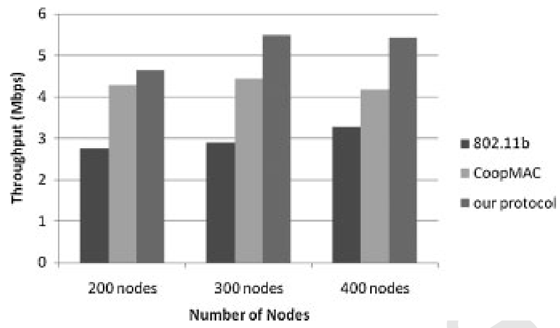

Fig. 11. ~~Throughput~~ of the three protocols ~~with different number of nodes~~.

5. CONCLUSIONS

In this paper, we propose a cross-layer MAC protocol which allows cooperative data retransmission. With the three new messages, the main cooperative retransmission protocol including both route enhancement and route bypass operations are implemented. The overall transmission reliability is maintained by allowing relay nodes be dynamically added into the route. Besides, both the number of data transmissions and communication hops are reduced through route bypass operations. Simulation results show that our cooperative retransmission scheme outperforms IEEE 802.11b DCF and CoopMAC protocols in terms of retransmission rate, hop count, and throughput.

REFERENCES

1. Sendonaris A, Erkip E, Aazhang B. Increasing uplink capacity via user cooperation diversity. *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, August 1998; 156.
2. Yi Z, Kim M. Diversity order analysis of the decode-and-forward cooperative networks with relay selection. *IEEE Transactions on Wireless Communications* 2008; **7**(5): 1792–1799.
3. Ibrahim AS, SadekE AK, Su W, Liu K-JR. Cooperative communications with relay-selection: when to cooperate and whom to cooperate with? *IEEE Transactions on Wireless Communications* 2008; **7**(7): 2814–2827.
4. Bletsas A, Khisti A, Reed DP, Lippman A. A Simple cooperative diversity method based on network path selection. *IEEE Journal on Selected Areas in Communications* 2006; **24**, (3): 659–672.
5. Shi Y, Sharma S, Hou YT. Optimal relay assignment for cooperative communications. *Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'08)*, May 2008; 3–12.
6. Mahinthan V, Cai L, Mark JW, Shen X. Partner selection based on optimal power allocation in cooperative-

diversity systems. *IEEE Transactions on Vehicular Technology* 2008; **57**, (1): 511–520.

7. Lichte HS, Valentin S, Karl H, Aad I, Loyola L, Widmer J. Design and evaluation of a routing-informed cooperative MAC protocol for ad hoc networks. *Proceedings of 27th Conference of the IEEE Computer and Communications Societies (INFOCOM 2008)*, April 2008; 1858–1866.
8. Beres E, Adve R. Cooperation and routing in multi-hop networks. *Proceedings of IEEE International Conference on Communications (ICC 2007)*, June 2007; 4767–4772.
9. Yan L, Hailes S. Cooperative packet relaying model for wireless ad hoc networks. *Proceeding of the ACM International Workshop on Foundations of Wireless Ad Hoc and Sensor Networking and Computing (FOWANC '08)*, May 2008; 93–99.
10. IEEE Std. 802.11b-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer Extension in the 2.4GHz Band, 1999.
11. Zhao B, Valenti MC. Practical relay networks: a generalization of hybrid-ARQ. *IEEE Journal on Selected Areas in Communications* 2005; **23**, (1): 7–18.
12. Dianati M, Ling X, Naik K, Shen X. A node cooperative ARQ scheme for wireless ad hoc networks. *IEEE Transactions on Vehicular Technology* 2006; **55**, (3): 1032–1044.
13. Zhu H, Cao G. rDCF: a relay-enabled medium access control protocol for wireless ad hoc networks. *IEEE Transactions on Mobile Computing* 2006; **5**, (9): 1201–1214.
14. Liu P, Tao Z, Narayanan S, Korakis T, Panwar SS. CoopMAC: a cooperative MAC for wireless LANs. *IEEE Journal on Selected Area in Communications* 2007; **25**, (2): 340–354.
15. Shan H, Wang P, Zhuang W, Wang Z. Cross-layer cooperative triple busy tone multiple access for wireless networks. *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM 2008)*, November 2008; 1–5
16. The Network Simulator ns-2. Available at: www.isi.edu/nsnam/ns
17. Johnson DB, Maltz DA, Hu YC. The dynamic source routing protocol for mobile ad hoc networks (DSR). *IETF MANET Working Group Internet-Draft*, April, 2003.
18. Camp T, Boleng J, Davies V. A survey of mobility models for[Q3] ad hoc network research. ~~*Wireless Communications and Mobile Computing* 2002; 483–502~~.

Authors' Biographies

Jeng-Long Chiang received the B.S degree (1999) in Computer Science and Information Engineering from National Chiao Tung University, Taiwan, and the M.S. degree (2001) in Computer Science from National Tsing Hua University, Taiwan. He is currently a Ph.D candidate in the Department of Computer Science, National Tsing Hua University, Taiwan. His current research interests include peer-to-peer networks, wireless networks, and network quality of services.

Jang-Ping Sheu received the B.S. degree in Computer Science from Tamkang University, Taiwan, Republic of China, in 1981, and the M.S. and Ph.D. degrees in Computer Science from National Tsing Hua University, Taiwan, Republic of China, in 1983 and 1987, respectively. He is currently a Chair Professor of the Department of Computer Science, National Tsing Hua University. He was a Chair of Department of Computer Science and Information Engineering, National Central University from 1997 to 1999. He was a Director of Computer Center, National Central University from 2003 to 2006. His current research interests include wireless communications and mobile computing. He was an associate editor of IEEE Transactions on Parallel and Distributed Systems and Journal of Information Science and Engineering. He is an associate editor of International Journal of Ad Hoc and Ubiquitous Computing and International Journal of Sensor Networks. He received the Distinguished Research Awards of the National Science Council of the Republic of China in 1993–1994, 1995–1996, and 1997–1998, the Distinguished Engineering Professor Award of the Chinese Institute of Engineers in 2003, the K.-T. Li Research Breakthrough Award of the Institute of Information and Computing Machinery in 2007, and the Y. Z. Hsu Scientific Chair Professor Award in 2009. Dr Sheu is an IEEE Fellow.

Huan-Chun Tseng received the Master degree in Computer Sciences from the National Tsing Hua University, Taiwan, R.O.C. in 2009. His research interests include wireless sensor networks and wireless ad hoc networks.

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Wen-Tsuen Chen received the[Q4] B.S. degree in Nuclear Engineering from National Tsing Hua University, Taiwan, and the M.S. and Ph. D. degrees in Electrical Engineering and Computer Sciences both from University of California at Berkeley, in 1970, 1973, and 1976, respectively. He has been with the National Tsing Hua University since 1976 and is currently a Distinguished Chair Professor of the Department of Computer Science. He has served as Chairman of the Department, Dean of College of Electrical Engineering and Computer Science, and President of National Tsing Hua University. His research interests include computer networks, wireless Internet, multimedia communications, and parallel algorithms. Dr Chen received numerous awards for his academic accomplishments in computer networking and parallel processing, including Outstanding Research Award National Science Council, Academic Award in Engineering from the Ministry of Education, Technical Achievement Award of the IEEE Computer Society, and is currently a National Chair Professor of the Ministry of Education, Taiwan. Dr Chen was the General Chair of the 2000 IEEE International Conference on Distributed Computing Systems and the Founding General Chair of the IEEE International Conference on Parallel and Distributed Systems. He is an IEEE Fellow and Fellow of the Chinese Technology Management Association.

Q4

A MAC protocol with cooperative retransmission is proposed to enhance the performance of mobile ad hoc networks. The cross-layer route enhancement and route bypass mechanisms dynamically adapt route path so as to allow data packets to be transmitted on reliable path with fewest duplicated retransmissions. Simulation results show that the proposed protocol outperforms previous works in terms of increased transmission reliability and reduced delay time.