

Performance Evaluation of a Cooperative MAC Protocol at Ad Hoc Networks

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Abstract—Many researches have been done to enhance system performance of ad hoc networks up to now, one of which is cooperative communications. In this paper, a cooperative MAC protocol called CO-MAC is proposed and its performance is evaluated with simulation and analysis. System throughput and average access delay are used as performance measures. Numerical results show that this scheme provides more enhanced system throughput and lower average access delay than DCF scheme, which is the key protocol in IEEE 802.11 standard, and rDCF scheme, especially when frame transmission error probability is high.

Keywords—Cooperative MAC, WLAN, CRTS, helper node, CO-MAC, DCF

I. INTRODUCTION

Compared with conventional wireless LAN or mobile network, ad hoc networks are kinds of more advanced networks because homogeneous terminals directly communicate with each other over wireless channel at those networks [1]. However, all wireless networks including ad hoc networks have several disadvantages such as limited bandwidth, compared with wired networks. Therefore, one of the most challenging problems is how to improve system performance, which problem becomes how to increase frame transmission rate at data link layer. To achieve this higher transmission rate, the receiver is required to improve received SNR value or receiver capability itself. The IEEE 802.11 WLAN standard including the physical and data link layers is widely deployed since its DCF functionality based on CSMA/CA provides good performance, by resolving hidden terminal and exposed terminal problems.

To improve the system performance, recent wireless networks such as WiMax and WLAN, use link adaptation schemes. In order to implement these schemes, the most appropriate combination among various modulation and channel coding schemes is referred to be used under a specific channel condition. For instance, since 64-QAM can transmit three times faster than QPSK over the same bandwidth, 64-QAM is chosen to increase transmission rate in the better channel, while QPSK is used in the worse channel because QPSK is more bearable for transmission error than 64-QAM.

Cooperative communications are based on link adaptation schemes to improve system performance much more. Fig. 1

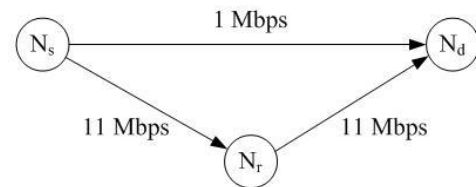


Figure 1. Example of cooperative communication

represents a simple network consisting of a source node(N_s), a destination node(N_d), and a helper node(N_r). Let's suppose that frame relaying capability at the helper node makes it possible to transmit frames at a rate of 11 Mbps from N_s to N_r , and from N_r to N_d , while direct link from N_s to N_d provides only 1 Mbps due to its worse channel status. In this case, average transmission rate through the helper node becomes $\frac{11 \times 11}{11 + 11} = 5.5$ Mbps, which is better than 1 Mbps, the transmission rate over the direct path. Thus, cooperative communication enhances system capacity by reducing the packet transmission time through a helper node with better channel status.

In this paper, we propose a cooperative MAC protocol called CO-MAC (cooperative MAC) protocol which can provide enhanced performance especially when frame transmission error probability is high, and evaluate its performance. The survey of related researches is described in Section II and the proposed CO-MAC protocol is described in the Section III. Its performance is evaluated with mathematical equations and computer simulation in the Section IV and its numerical results are represented in Section V, and then this paper is concluded in Section VI.

II. RELATED WORKS

Most of recent researches for cooperative MAC protocol at ad hoc networks are based on IEEE 802.11 WLAN protocol [1] [2]. In addition, IEEE 802.16e called mobile WiMax, IEEE 802.11a, and IEEE 802.11g use the link adaptation scheme which chooses a modulation and channel coding scheme based on the current channel status (i.e., received SNR value). The receiver-based auto rate (RBAR) scheme which determines the

frame transmission rate based on the channel quality measured in the receiver node is proposed in [3].

Based on currently deployed wireless LAN protocol, various cooperative MAC protocols are suggested [4]- [10]. The rPCF (relay PCF) scheme which is a cooperative MAC protocol based on PCF scheme of IEEE 802.11 WLAN is proposed [4]. In this scheme, every terminal should check all frames from adjacent nodes, store related channel information (i.g., received SNR value) between each adjacent node and itself, and inform the AP of those collected information. Then, the AP gives the transmission chance to each terminal by sending CF-Poll frame, which contains transmission rate among the source, the destination and helper nodes. However, rPDF is complicated because AP should manage all channel information between all adjacent nodes and itself. In addition, rPCF could cause another problem since it assumes that every node can communicate directly each other but it doesn't in the existing PCF scheme.

CMAC protocol and FCMAC protocol which is a combined version of CMAC protocol and an error control scheme are proposed in [5]. This cooperative MAC protocol can be implemented with a little modifications from current IEEE 802.11 WLAN standard which is one of advantages, but it doesn't specify how to select helper nodes. A new ARQ scheme for cooperative communication is suggested in [6], [7]. In [6], the destination node requests the retransmission by sending NACK when it couldn't receive correct data frame from the source node due to transmission error. At that time, to reduce the transmission time, one of neighbor nodes can retransmit the same data frame instead of the source node. This research focuses on cooperative retransmission rather than cooperative communication but its performance is evaluated clearly by mathematical equations. In [7], three different ARQ schemes are studied according to the retransmitting node and the retransmitting method. In [8], rDCF scheme which is based on DCF protocol is proposed. In this protocol, every node calculates the received SNR value (or corresponding frame transmission rate) of the wireless channel from the source node to the helper node by checking the received frame. They store the SNR values in its willing list and share the list with other adjacent nodes by sending this list periodically. Nodes which receives the willing list stores it in its relay table. Whenever a packet is generated in a source node, the relay table is searched to find a helper node which can provide more effective transmission link than direct transmission link between the source node and the destination node. If there exists an appropriate helper node between the source node and destination node, then, the source node transmits RRTS1 (Relay RTS1) frame for cooperative communication to the helper node rather than to the destination node. A cooperative MAC protocol called CODE, which extends rDCF to use two helper nodes for diversity gain, is proposed in [9]. CODE protocol surpasses rDCF protocol since two helper nodes support cooperative communications but this scheme uses the same procedure in selecting helper nodes with the rDCF protocol. However, it is not appropriate that CODE compares its performance with

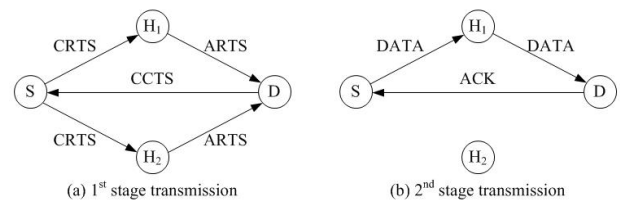


Figure 2. Two-stage CO-MAC protocol

RBAR scheme, not rDCF protocol. CoopMAC which has different procedures to transmit control frames is proposed in [10]. CoopMAC explains clearly its procedure to choose helper nodes by mathematical equations.

Conventional DCF protocol is analyzed by queuing theory in [11] and its performance is evaluated under the saturated condition that all nodes always have packets to transmit in their buffers. Thus the calculated throughput in that paper is also called maximum system throughput, or system throughput of saturated condition. Cooperative MAC protocols of [8]- [10] are evaluated by using the model in this paper. However, this model has one defect that each terminal retransmits its frame until it succeeds in its transmission. Tantra [12] uses the modified model in which each terminal discards its frame if the number of retransmissions for this frame exceeds the maximum retransmission number specified in the IEEE 802.11 standard.

After surveying those related researches, we discover two non-trivial problems. First, most of protocols compare their performances with RBAR or IEEE 802.11 WLAN, not with recent cooperative MAC protocols. Second, for their performance evaluation, they assume that transmission channels are error-free.

III. CO-MAC PROTOCOL

The CO-MAC (Cooperative MAC) protocol proposed in this paper consists of two-stage transmissions represented as Fig. 2. The first stage is to exchange control frames such as CRTS (Cooperative RTS), ARTS (ACK RTS) and CCTS (Cooperative CTS). The traditional CSMA/CA scheme in IEEE 802.11 WLAN is adapted to transmit CRTS in this stage. It is assumed that the source node knows in advance all candidate helper nodes to cooperate. How to select helper nodes is the same with [8]- [10]. That is, every node manages its own willing list to see available transmission rate and channel status to all adjacent nodes. Then, every node broadcasts those collected channel information periodically to neighboring nodes to share it. Each node who receives the willing list from adjacent nodes updates its C-table (cooperative table) with helper node ID, available transmission rate, and etc. The second stage represents the procedure that the source sends its DATA frame through the selected helper node and receives the ACK frame from the destination node. Basically CO-MAC protocol is designed based on DCF scheme. Fig. 3 shows how the four nodes communicate their control and data frames in detail, respectively.

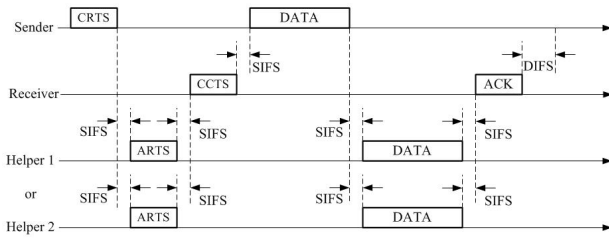


Figure 3. Frame exchange at CO-MAC protocol

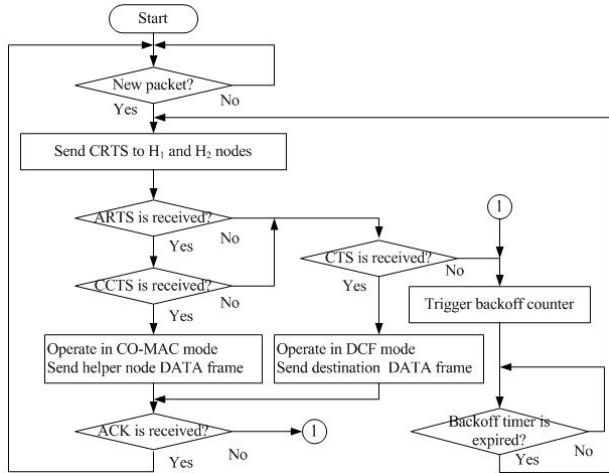


Figure 4. Flow chart at source nodes

From now on, work procedure at source nodes, destination nodes and helper nodes are described in detail. Flow chart for source nodes is represented as Fig. 4. When a new packet is generated, the source node starts to contend with the other nodes for seizing wireless channel to transmit the packet. CRTS frames, which are re-designed for CO-MAC protocol, are used for the contention. CRTS frames include MAC addresses of the destination node and two helper nodes. Possible transmission rates between those nodes (e.g., R_{sh} , R_{hd} , R_{sd}) are included in CRTS frame headers, too. In this case, R_{sh} means the transmission rate between the source node (S) and the helper node (H). The RRTS1 frame in [8] is expected to have similar header format with CO-MAC but this surmise cannot be confirmed since the RRTS1 format is not described in that paper. When the source node receives the ARTS frame transmitted by one of helper nodes to the destination node in SIFS duration after sending the CRTS frame, it waits for the CCTS frame from the destination node. If this source node receives the CCTS frame, then it sends the DATA frame to the helper node and waits for the ACK frame. Overall transmission is completed when the ACK frame is received from the destination node. If the ACK frame is not received in time, the source node tries its retransmission by triggering its back-off counter. How to use back-off counters is the same with the procedure described in the conventional IEEE 802.11 standard. The header in DATA frame needs to include MAC addresses of the destination node in addition to

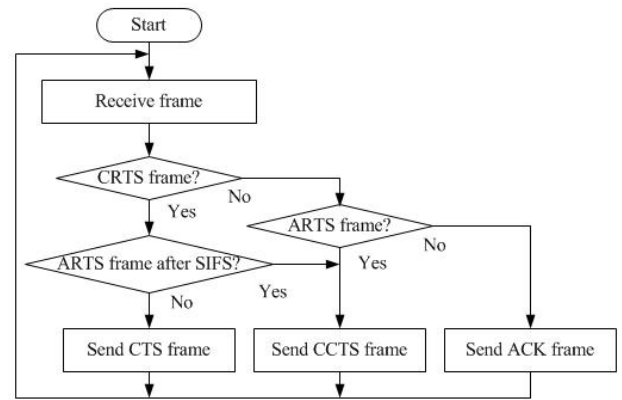


Figure 5. Flow chart at destination nodes

that of the helper node. Existing DCF, instead of CO-MAC protocol, will work when the CTS frame is received at the source node side.

How destination nodes work is described in Fig. 5. The destination node waits for the ARTS frame when it receives the CRTS frame from the source node. It sends the CCTS frame to the source node if it receives the ARTS frame within the designated time. It calculates the achievable transmission rates based on the received SNR values of the CCTS and ARTS frames and inserts the information on those rates into the CCTS frame. The CTS frame is transmitted if it doesn't receive the ARTS frame. The destination node sends the ACK frame to the source node when the DATA frame is successfully received.

Flow chart for helper nodes is represented as Fig. 6. The helper node whose address is located at the forward part of the CRTS frame header has higher priority. Let's assume that the helper node H_1 has higher priority here. Then, H_1 checks whether it can participate in this cooperative communication when it receives the CRTS frame. If it can (i.e., it decides whether transmission rate R_{sh_1} included in the CRTS frame is achievable based on the measured SNR value of the received the CRTS frame), then it sends the ARTS frame. If the helper node cannot, then it stays in an idle state. Then, another helper node H_2 checks if H_1 participates in the cooperative communication by checking whether H_1 sends the ARTS frame in SIFS duration after the arrival of the CRTS frame. If H_2 doesn't hear the ARTS frame transmitted from H_1 and it can transmit data frame at R_{sh_2} described in the CRTS frame, it participates in this cooperative communication by sending the ARTS frame. When the DATA frame is received from the source node, then this helper node forwards the DATA frame to the destination node.

IV. PERFORMANCE EVALUATION

We adopt the queuing theory based analytic method which Tantra used in [12]. The method is used to get maximum throughput in the saturated condition. In this paper, it is assumed that there can be transmission error only for CRTS

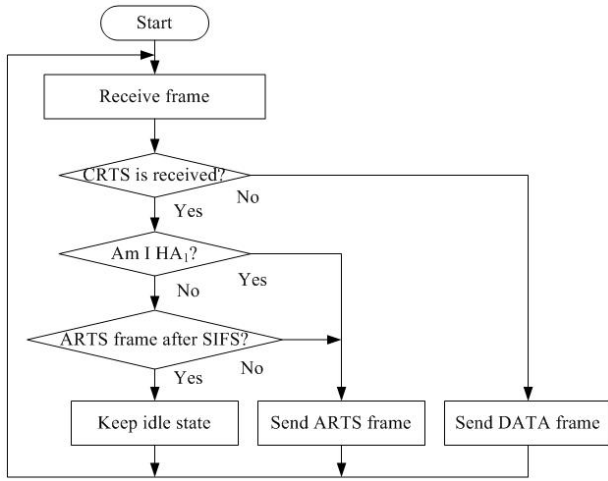


Figure 6. Flow chart at helper nodes

frames, which the source nodes transmit for channel contention. This performance evaluation is assumed to be limited only into a single cell and, therefore, hidden/exposed terminal problems are not considered here. In addition, it is assumed for simplicity that communication circumstances at two helper nodes are the same and thus collision and error probabilities experienced at those two nodes are the same, too.

First of all, let's define several variables used in this performance evaluation.

- τ : CRTS frame transmission probability at a node
- n : total number of nodes which are within a transmission range from a source node
- p_c : collision probability of an CRTS frame
- p_e : transmission error probability of an CRTS frame due to bad channel status
- p_f : transmission failure probability of an CRTS frame due to bad channel status or collision
- m : maximum backoff stage of contention window where $CW_{\max} = 2^m CW_{\min}$
- r : maximum number of retransmissions at a binary exponential backoff scheme

Transmission failure of CRTS frames can be caused by either CRTS frame collision or transmission error. This probability can be described as $p'_f (= p_e + p_c - p_c p_e)$ in case of rDCF, CODE or CoopMAC protocols. However, this probability is represented as $p_f (= p_e^2 + p_c - p_c p_e^2)$ for CO-MAC protocol because transmission error for a CRTS frame occurs only when two helper nodes H_1 and H_2 fail in receiving this CRTS frame due to channel error. The size of contention window used in CO-MAC protocol is represented as following:

$$W_i = \begin{cases} 2^i CW_{\min} & 0 \leq i \leq m \\ 2^m CW_{\min} & m < i \leq r \end{cases} \quad (1)$$

Then, CRTS frame transmission probability at a node τ can be derived as Eq. (2) from [12].

$$\tau = \sum_{i=0}^r \alpha_{i,0} = \frac{1 - (p_f)^{r+1}}{1 - p_f} \alpha_{0,0} \quad (2)$$

where $\alpha_{i,j}$ means a steady-state probability of the 2-dimensional transition rate diagram described in [12]. And $\alpha_{0,0}$ can be computed from the requirement that the sum of all steady-state probabilities $\alpha_{i,j}, 0 \leq i \leq W_i - 1, 0 \leq j \leq r$ becomes one. Then, the CRTS frame transmission probability at a node τ can be calculated by using Eq. (2) and the other independent Eq. (3).

$$\begin{aligned} p_c &= 1 - (1 - r)^{n-1} \\ p_f &= p_e^2 + p_c - p_c p_e^2 \end{aligned} \quad (3)$$

The probability that n communication terminals transmit at least one CRTS frame over the wireless channel based on CSMA/CA P_{tr} is represented as Eq. (4).

$$P_{tr} = 1 - (1 - \tau)^n \quad (4)$$

On the other hand, the probability that a CRTS frame is transmitted without both collision and transmission error, given that n communication terminals transmit at least one CRTS frame over the wireless channel, is represented as Eq. (5).

$$P_s = \frac{n\tau(1 - \tau)^{n-1}}{P_{tr}} (1 - p_e^2) \quad (5)$$

After then, the average time the channel is sensed busy (i.e., the slot time lasts) because of a successful transmission T_s^{CO} and the average time the channel is sensed busy by each station during a collision T_c^{CO} are represented as Eq. (6) and Eq. (7).

$$\begin{aligned} T_s^{CO} &= CRTS + ARTS + CCTS \\ &\quad + DATA(L, R_{sh}) + DATA(L, R_{hd}) + ACK \\ &\quad + 5SIFS + 6\delta + DIFS \end{aligned} \quad (6)$$

$$T_c^{CO} = CRTS + DIFS + \delta \quad (7)$$

In Eq. (6), $DATA(L, R_{sh})$ is the time spent for transmitting the DATA frame with length L at the transmission rate R_{sh} . $CRTS$, $ARTS$, $CCTS$, and ACK mean time durations spent for transmitting those frames at the basic transmission rate, which is 1 Mbps as shown in Table I. For simplicity, propagation delay among nodes δ is not considered in this paper. Then, the system throughput of CO-MAC protocol, typical performance measure, can be derived as Eq. (8).

$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_s P_{tr} T_s^{CO} + P_{tr}(1 - P_s) T_c^{CO}} \quad (8)$$

In the above equation, $E[P]$ means $DATA(L, R_{avg})$ where R_{avg} is $(R_{sh} + R_{hd})/2$ and σ is the length of idle slot.

The average access delay is used as another performance measure here. This measure is defined as average waiting time of a DATA frame in the buffer at the source node between its arrival to the buffer and the time instant when

the source node succeeds in catching the wireless channel for transmitting this DATA frame. In this case, the probability that a CRTS is transmitted successfully after i retransmissions can be represented as Eq. (9).

$$P_s(i) = (p_f)^i(1 - p_f), \quad 0 \leq i \leq r \quad (9)$$

Then, average access delay in a unit of slots can be derived as Eq. (10).

$$D = \begin{cases} \sum_{i=0}^r P_s(i) \frac{W}{2} \sum_{j=0}^i 2^j, & r \leq m \\ \sum_{i=0}^m P_s(i) \frac{W}{2} \sum_{j=0}^i 2^j + \sum_{i=m+1}^r P_s(i) \cdot \frac{W}{2} \left\{ \sum_{j=0}^m 2^j + \sum_{j=m+1}^i 2^m \right\}, & r > m \end{cases} \quad (10)$$

V. NUMERICAL RESULTS

It is assumed that there are n nodes in the communication network considered for performance evaluation. But only four nodes consisting of a source node, a destination node, and two helper nodes, such as Fig. 2, are focused on here. System parameters used in performance evaluation are described in Table I. All control frames are transmitted at the basic rate (i.e., 1 Mbps) and DATA frames can be transmitted at different transmission rate based on received SNR value. It is assumed here that the direct path between the source node and the destination node provides only the basic rate but that transmission path between helper nodes and source or destination nodes can provide 11 Mbps. Thus, in case of CO-MAC or rDCF protocol, system throughput denoted in Mbps can be obtained by multiplying 11 Mbps to Eq. (8) while in case of DCF by multiplying 1 Mbps because DATA frames in DCF protocol are transmitted directly between the source node and the destination node.

Table I
SYSTEM PARAMETERS

Parameter	Value	Parameter	Value
CRTS length	352 bits	SIFS	10 μ s
ARTS length	352 bits	DISF	50 μ s
CCTS length	304 bits	CWmin	31 slots
ACK length	304 bits	CWmax	1023 slots
DATA length	1024 bytes	retryLimit(m)	6
Slot duration (σ)	20 μ s	R_{sh} , R_{hd}	11 Mbps
RTS/CTS length	160/112 bits	Basic Rate	1 Mbps

Fig. 7 and Fig. 8 shows the performance of the proposed CO-MAC protocol. Fig. 7 depicts analytic and simulated numerical results on various transmission error environments as a function of the number of nodes. According to those results, since the number of nodes increases, the throughput decreases. That is because more nodes cause higher probability for collision in the saturated condition. But reference [10] insists that, in general, cooperative communication makes the throughput increase to a certain point as the number of nodes increases. That is because increased number of nodes in a network means the increased possibility of helper nodes with better channel condition between source nodes and destination

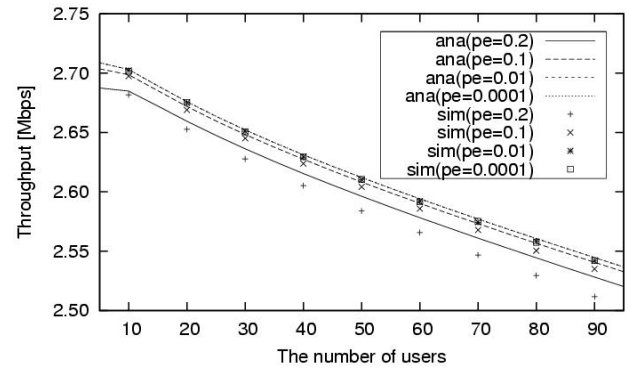


Figure 7. System throughput as a function of the number of nodes

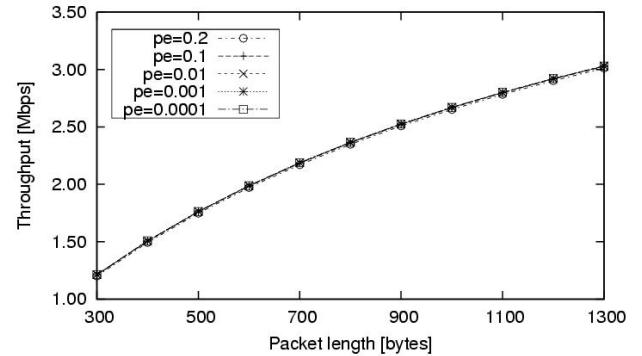


Figure 8. System throughput as a function of DATA frame length

nodes. In this paper, however, the link transmission rates between the helper nodes and the other nodes are fixed as 11 Mbps, the maximum transmission rate. Therefore, there is no space to be enhanced anymore with increasing number of nodes.

Fig. 8 depicts how the throughput changes as the data frame length varies over various transmission error probabilities, when the number of nodes is fixed as 10. As the size of DATA frame increases, the overhead ratio of control frames to DATA frames decreases and thus system throughput increases. Numerical results in Fig. 8 look like nearly the same over different frame transmission errors. However, this is only due to increased throughput ranges (from 1 Mbps to 3.5 Mbps) compared to Fig. 7 (from 2.5 Mbps to 2.75 Mbps).

The system throughput of CO-MAC is compared with rDCF [8] in Fig. 9. CO-MAC represents obviously better performance as transmission error probability increases, because CO-MAC has one more helper node rather than rDCF protocol.

Fig. 10 compares the throughput of CO-MAC with DCF and rDCF protocols according to the various DATA frame sizes. DCF works with relatively low throughput because the source node is assumed to communicate with the destination node only at 1 Mbps due to bad and relatively longer distance between them.

Fig. 11 compares the average access delay of CO-MAC with rDCF protocols as a function of transmission error probability.

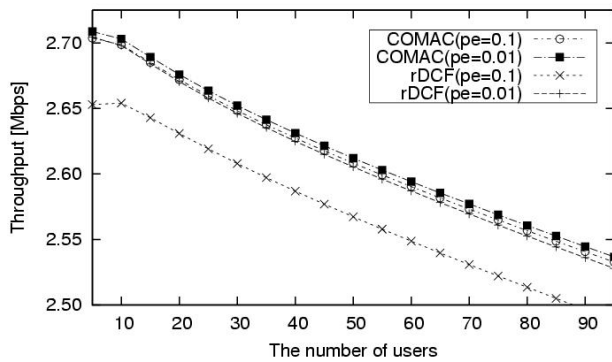


Figure 9. System throughput comparison between CO-MAC and rDCF

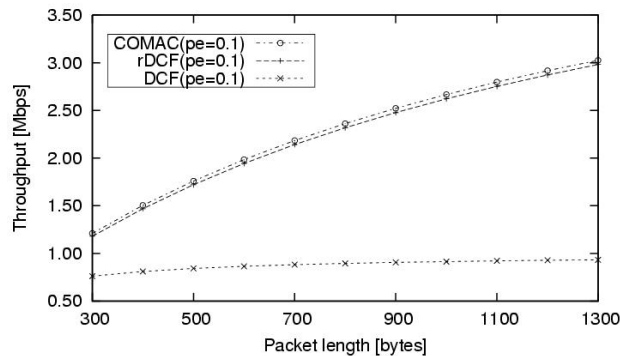


Figure 10. System throughput comparison among different protocols

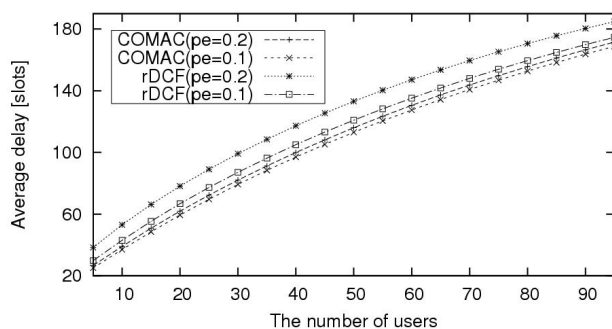


Figure 11. Average access delay comparison among different protocols

It is easy to understand that average access delay increases when the number of users in this network increases or when transmission error probability becomes greater. According to this figure, CO-MAC protocol provides smaller average access delay than rDCF protocol.

VI. CONCLUSION

In this paper we proposed a new cooperative MAC protocol named as CO-MAC and evaluate its performance by analysis. The advantage of the protocol proposed here is that it can provide enhanced system throughput and smaller average access delay with using almost the same network resource as rDCF protocol, especially when frame transmission error probability is high. We adopted Trantra model [12] and considered an erroneous channel between the source node and helper node.

Numerical results show that CO-MAC provides much more increased system throughput than DCF scheme in IEEE 802.11 standard. When wireless channel is noisy, it also has more enhanced system throughput and smaller average access delay than rDCF scheme from those results, too.

Obtaining various numerical results with computer simulation under more dynamic scenarios is reserved for the further research.

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