Cooperative MAC Protocol Using Active Relays for Multi-Rate WLANs

Chang-Yeong Oh and Tae-Jin Lee

Abstract: **Cooperative communications using relays in wireless networks have similar effects of multiple-input and multiple-output without the need of multiple antennas at each node. To implement cooperation into a system, efficient protocols are desired. In IEEE 802.11 families such as a/b/g, mobile stations can automatically adjust transmission rates according to channel conditions. However throughput performance degradation is observed by low-rate stations in multi-rate circumstances resulting in so-called performance anomaly. In this paper, we propose active relay-based cooperative medium access control (AR-CMAC) protocol, in which active relays desiring to transmit their own data for cooperation participate in relaying, and it is designed to increase throughput as a solution to performance anomaly. We have analyzed the performance of the simplified AR-CMAC using an embedded Markov chain model to demonstrate the gain of AR-CMAC and to verify it with our simulations. Simulations in an infrastructure network with an IEEE 802.11b/g access point show noticeable improvement than the legacy schemes.**

Index Terms: **Cooperative communications, IEEE 802.11, multiple access control (MAC), multi-rate, relay, throughput, wireless local area network (WLAN).**

I. INTRODUCTION

Cooperative communications, i.e., stations located within transmission range share their antennas and resources, is proposed to enhance performance [1]. It has the concept of a virtual multiple-input multiple-output (MIMO) system since antenna diversity gain in a MIMO system is similarly achieved by cooperation among single-antenna nodes, and it has the advantages of higher transmission rate, improved reliability, lower transmission delay, more efficient power consumption and extended coverage without multiple antennas at each node [2].

In recent researches, cooperative communications not only at the physical layer but also at higher layers of the protocol stack, e.g., the medium access control (MAC), or network layer, is proposed [3]. We focus on a MAC layer protocol for efficient cooperation in wireless local area networks (WLANs) based on IEEE 802.11 distributed coordination function (DCF). In [4] and [5], a source first transmits its own data by IEEE 802.11 DCF and a helper node relays the data of the source after the backoff process if the transmission of the source fails. So cooperative communications plays a role of automatic repeat request (ARQ) scheme extending that of legacy IEEE 802.11. Cooperative ARQ scheme aims at reducing packet transmission delay with improved reliability through relaying, and increasing network throughput. However, the cooperative transmission is used in a limited way, and the overhead to relay needs to be reduced for further improvement.

There may be performance anomaly due to the characteristics of carrier sense multiple access/collision avoidance (CSMA/CA) with the binary exponential backoff (BEB) algorithm in IEEE 802.11a/b/g to support multi-rate transmissions [7]. Regardless of transmission rates of mobile stations, probabilities of channel access are the same in CSMA/CA. Once a mobile station achieves channel access opportunity, mobile stations with lower rates occupies more channel time than those with higher rates. So the more mobile stations transmit with lower rates, the lower the overall network throughput becomes. That is, total network throughput is more influenced by the mobile stations with lower rates in multi-rate WLANs. Time-based fairness, i.e., each competing station receives an equal share of the wireless channel occupancy time, is proposed to solve this performance anomaly in multi-rate WLANs, which is generally achieved by controlling the size of MAC service data unit size (MSDU) or the initial contention window size [8], [9]. We call them different MSDU adaptation (DMA) and different initial contention window size adaptation (DICWA), respectively.

Compared to the legacy IEEE 802.11, DMA can enhance the utilization of channel time of the stations with higher rates, which has an effect of making stations share equal channel time. So, DMA can be a technique to improve overall network throughput. DICWA is another technique, which is intended to provide discriminative transmission chances according to different rates. If the stations with higher rates operate the BEB algorithm with smaller contention window size, and those with lower rates do with larger contention window size, more transmission opportunities are given to higher-rate stations. Thus, higher-rate stations will have more frequent chances to hold channel. As a result higher-rate stations can have increased channel occupying time. There has been an approach to optimally combine them [10].

In addition, cooperative communications in multi-rate WLANs can be an efficient technique to enhance the performance of low-rate stations with the aid of helpers, i.e., higher-rate stations [11], [12]. Authors in [11] propose CoopMAC with table-based proactive relay selection at a source, in which a low-rate station uses a helper that is located between the sender and the receiver, and it is able to transmit at a higher rate in a two-hop

Manuscript received April 6, 2010; approved for publication by Sunghyun Choi, JCN Editor, May 12, 2011.

This research was supported by PRCP through NRF of Korea, funded by MEST (2011-0018397), and the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency) (NIPA-2011-(C1090-1111-0005)).

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A preliminary version of this work was presented at WOCN'09 [6].

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manner. CoopMAC may not be effective for the time-varying wireless channel due to table update. In [12], CRBAR with reactive relay selection at a receiver is introduced and frame combining technique is used for diversity gain at the physical layer. However, relay nodes sacrifice their resource, e.g., power, channel, for cooperation, which requires compensation. Both are targeting at improving throughput rather than reliability by frequent utilization of relaying.

For cooperative communications in the MAC layer, two of the most important issues are how to cooperate and who to be helpers. In addition, we should consider the compensation mechanism for the helper which has provided cooperation. In this paper, the objective of our proposal is not only to solve the performance degradation problem in multi-rate IEEE 802.11 WLANs by boosting the transmission rate of low-rate stations through cooperation but also to compensate for relay stations by providing extra transmission chances. So, we propose to use active relays which have their own data to transmit (see Fig. 1). When the cooperative transmission is desirable, an active relay station receives the data of a source and relays it after combining it with the relay's own data to increase channel utilization.

The remaining part of this paper is organized as follows. Section II describes a novel MAC protocol, active relay-based cooperative medium access control (AR-CMAC). Section III gives an analytical model of AR-CMAC. Section IV presents performance evaluation to demonstrate the effectiveness of our proposal by simulations. In Section V, we conclude the paper.

II. PROPOSED ACTIVE RELAY-BASED COOPERATIVE MAC (AR-CMAC) PROTOCOL

AR-CMAC supports three modes according to the transmission type of the source's data: (i) *Direct transmission (DT)-(a)*, (ii) *DT-(b)*, and (iii) *cooperative transmission (CT)*. If a source can transmit with the highest rate, its own data need not be transmitted with the help of a cooperative relay. In this case, the transmission between a source and a destination is directly followed by the legacy IEEE 802.11 [13], i.e., DT-(a) mode. A station may not use a cooperative transmission if the station does not have appropriate relays for cooperation. In this case DT-(b) mode is used. Otherwise, the CT mode is desirable since it can provide shorter transmission time for the source's data by cooperation. We now elaborate the detailed operation of AR-CMAC.

A. Procedure of AR-CMAC

A.1 Cooperation Request

When an access point (AP) or a destination receives a request to send (RTS) frame from a source, the AP or the destination is aware of the transmission rate of data from the header information, and other nodes within the transmission range from the source can also overhear the RTS frame for network allocation vector (NAV) setup. If a source transmits with the highest rate, the AP or the destination responds to the source with a clear to send (CTS) frame and the next procedure is followed by the DT-(a) mode. Otherwise, the AP or the destination responses to the source with a cooperative CTS (cCTS) frame, which is newly a defined control frame with the same size as a CTS frame, to request cooperative communications (see

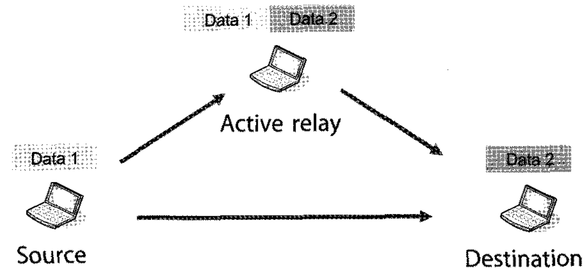

Fig. 1. Cooperative communications among source, relay, and destination.

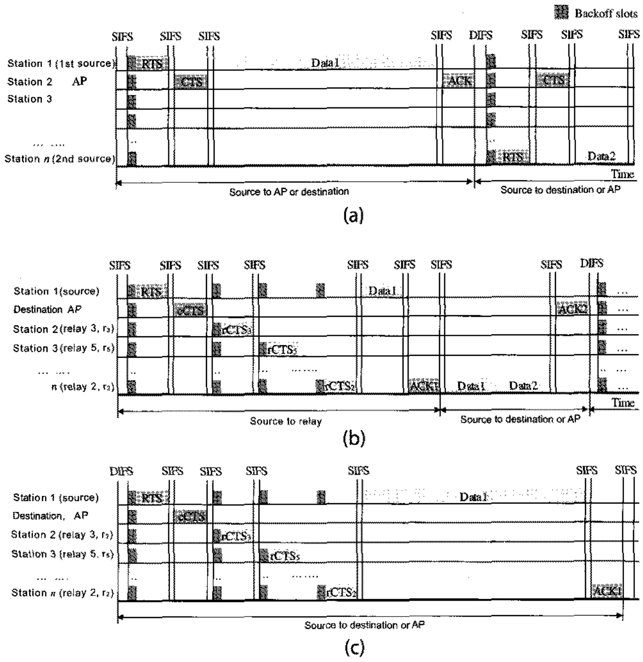

Fig. 2. The operation of AR-CMAC protocol and legacy IEEE 802.11: (a) An example of the legacy IEEE 802.11b with RTS/CTS or AR-CMAC direct transmission (DT)-(a) mode, (b) an example of AR-CMAC cooperative transmission (CT) mode, and (c) an example of AR-CMAC direct transmission (DT)-(b) mode.

Fig. 3(b)). The CTS and cCTS are differentiated by the subtype of the frame control (FC) field in the header. When CTS or cCTS is being sent, other nodes within the transmission range of the AP can also overhear CTS or cCTS as well.

A.2 Active Relay Selection

The nodes overhearing both RTS and cCTS are the candidate relays. Candidate relays i) must be within the effective transmission range from a source and a destination and ii) have higher rates than that of the source. The effective transmission range can be decided from the signal to noise ratio (SNR) of the received RTS and cCTS. The reason for the condition ii) is that higher-rate stations can play a role of relays to increase throughput. Each of candidate relays sends a relay CTS (rCTS) frame to the source after a random backoff time in order to indicate that it can operate as a relay of the source for cooperative communications. The rCTS frame is also a newly defined control frame (see Fig. 3(c)). The Rsr field of rCTS is filled with the achievable rate between the source and the relay from the estimated SNR by overhearing RTS. And, the Rrd field of rCTS is filled

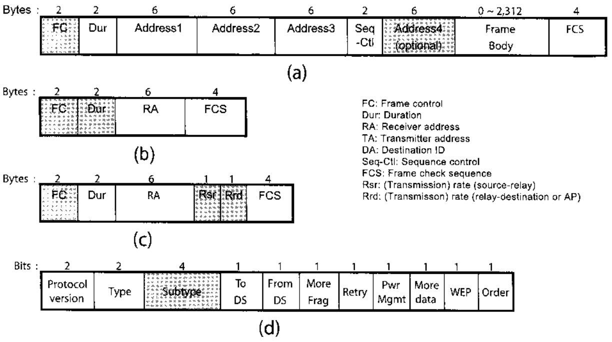

Fig. 3. Newly defined frames for proposed AR-CMAC: (a) Data format, (b) cCTS format, (c) rCTS format, and (d) FC field.

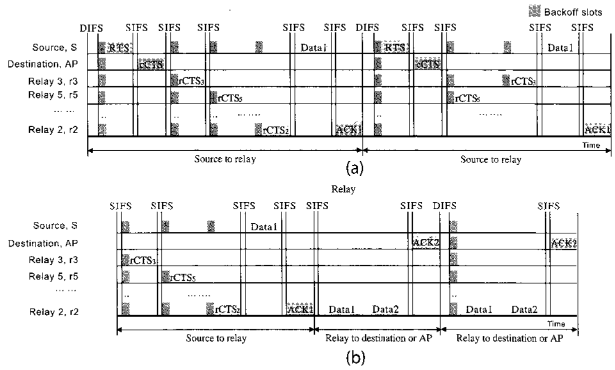

Fig. 4. Examples of operations when ACKs are not received: (a) Source fails to receive ACK1 and (b) the selected relay fails to receive ACK2.

with the recently successful transmission rate of the relay to the AP. A proper contention window size for sending rCTS frames (w_{rCTS}) is required to provide contention resolution among candidate relays. If w_{rCTS} is too large, there may be waste of time for the backoff operation. If it is too small, intensive competition may cause many simultaneously transmitted rCTSs resulting in a collision. And w_{rCTS} can be designed to vary according to the total number of nodes in a network.

If rCTSs are not received at all by the source due to no candidate relays or collision of rCTSs, the source cannot help using the direct transmission, i.e., DT-(b) mode. To protect from the frequent DT-(b) mode operation due to the absence of candidate relays, an AP sends CTS rather than cCTS in respond to RTS if there was not any transmitted rCTSs responding to the previous cCTSs. When the source receives rCTS frames, it chooses the most suitable relay among the candidate relays from the information in the rCTS frames. The issue is which relay is selected among them. Our simulations (see Fig. 12) indicate that choosing the highest-rate relay provides the greatest benefit in terms of throughput. So we select the relay with the highest rate. Now the source must know when all the transmissions of rCTSs are finished and its own data can be transmitted without collision against rCTSs. To solve this problem, we propose that the source itself also operates the BEB algorithm as well as candidate relays. However the source always chooses the maximum backoff value to transmit rCTSs ($BO^{\mathrm{Max}}_{\mathrm{rCTS}} = w_{\mathrm{rCTS}} - 1$) in contrast to those of candidate relays, i.e., randomly selected backoff values among $[0, w_{\mathrm{rCTS}} - 1]$. The $BO^{\mathrm{Max}}_{\mathrm{rCTS}}$ is fixed so that the source can forward its data after $BO^{\mathrm{Max}}_{\mathrm{rCTS}}$ elapses regardless of the number of candidate relays sending rCTSs. If at least one rCTS is successfully transmitted, the CT mode starts.

A.3 Data Transmission by Active Relay

After the source chooses the best relay based on the information of the rCTS frames, it sends a data frame to the selected best relay. The format of the data frame for the CT mode is defined in Fig. 3(a). We propose to use an optional field, *Address4*, to contain the MAC address of the best relay. To differentiate the new data frame with the legacy data frame, a new subtype is required in the FC field of a MAC header as in cCTS and rCTS. Now the issue is who sends an ACK frame to the source. In our AR-CMAC, we design the sender of an ACK frame is the selected best relay not the AP or the destination since the transmission rate of the source targets at the selected relay. So the reliable reception of the source data at the AP or the destination may be difficult. Furthermore when the retransmission of the source's data to the AP or the destination is required, the retransmission of the source's data to the selected relay and then to the AP or the destination is more efficient than to the AP or the destination since the feasible rate between the source and the AP or the destination is likely to be low. The best relay now sends back in response to the source's data. After ACK is transmitted, the selected relay decodes the data of the source and combines it with its own data. And it is finally forwarded to the AP or the destination by the selected relay to enhance channel utilization. Another ACK frame from the AP or the destination to the selected relay is sent to confirm the successful reception of data sent from the selected relay. In summary, an active relay station receives the source's data and retransmits it after combining it with the relay's own data to increase channel utilization whenever the cooperative transmission is desirable.

B. Advanced rCTS Transmission Scheme

In the active relay selection, we need to consider rCTSs overhead. The more rCTSs are sent, the lower the throughput becomes. So our approach is to find a way to decrease the number of the transmitted rCTSs. The key idea is to consider the nature of wireless channel: *Broadcasting and overhearing*. A candidate relay can overhear the rCTSs of other relays and compare the rate (between the relays and the AP or the destination) values in the Rrd field of the rCTS frames, with its own. If it is superior to those of other candidate relays, the candidate relay will transmit its own rCTS. Otherwise, it gives up transmitting its own rCTS. By this extension, the total number of transmitted rCTSs can be lessened.

C. Cases with No ACKs

When collision occurs or channel condition is bad, ACK may not be received at the sender. Now we represent two examples that ACK is not properly received at each sender as in Fig. 4. In the case of no ACK1, the current source must regain channel access to transmit Data1 through the backoff competition with other nodes after DCF interframe space (DIFS). Fig. 4(a) shows the case that the current source wins channel access again. In the case of no ACK2, the situation is similar because the selected relay must access channel by competition for retransmission. But in this case, the exchanges of RTS and CTS are not required. Fig. 4(b) shows the case that the selected relay wins.

D. NAV Setup

In order to protect the CT mode, appropriate NAV setup is required as described below. Once the channel is accessed by a source and the selected relay, the channel access should not be interrupted by others for the source, the selected relay and the AP or the destination. This protection can be achieved by the NAV setup by other nodes for the CT mode. We show the phase of the NAV setup and update for the CT mode in Fig. 5. The time duration in the Dur field of each frame for the NAV setup is given when w_{rCTS} is 8. In this example, rCTSs of relay r_3 and r_4 collide with each other and the transmission of rCTS of relay r_1 is successful. Other relays including relay r_2 give up the transmission of their own rCTSs because relay r_1 is in group 1.[1] When rCTSs are sent, the duration of the maximum transmission time is reflected in rCTSs. When Data1 is sent, the Dur field of Data1 contains the time duration information for protection.

E. Fragmentation

In AR-CMAC, support of fragmentation is essential because the sum of Data1 and Data2 may exceed the maximum MSDU size (2304 bytes [13]). If we cannot use the fragmentation technique, the maximum MSDU size of one transmission in AR-CMAC must be shortened to half (1152 bytes) of the legacy so that the sum of Data1 and Data2 does not exceed 2304 bytes. In the case that the size of data sent by a relay exceeds the maximum MSDU size, it can be fragmented because IEEE 802.11 supports fragmentation [13]. The AR-CMAC CT mode is supposed to use two fragments. Each fragment is transmitted with a new header according to the fragmentation policy of legacy 802.11.

F. Security

Some security issues may be concerned in AR-CMAC due to its nature, i.e., broadcasting, overhearing, and relaying. There has been research on the security issue to present solutions for cooperative communications based on the current security protocols, e.g., wired equivalent privacy (WEP), Wi-Fi protected access (WPA), and IEEE 802.11i (WPA2) [14] or to handle relay's misbehavior through cross-layer approach [15]. So security issues of AR-CMAC cooperative communications may be treated accordingly.

III. ANALYTICAL MODEL OF THE SIMPLIFIED AR-CMAC

In this section, we analyze the performance of the AR-CMAC using an embedded Markov chain model as described in Fig. 6 to demonstrate the performance gain of AR-CMAC and to verify it with our simulations. We assume that there exist two groups, e.g., high-rate group, low-rate group, in a network and the transmission rates of stations in the groups are 11 Mbps and 1 Mbps, respectively. And the transmission rate between a source and the relay is fixed to 5.5 Mbps. In addition, we consider the saturation

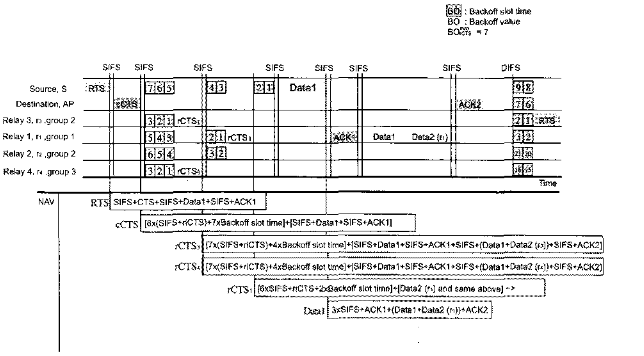

Fig. 5. NAV mechanism for CT mode protection.

condition, which means that there is always a new frame waiting for transmission at a station and there always exist candidate active relays. For analysis, we don't consider some schemes to further enhance the performance of AR-CMAC as described in the previous section, e.g., advanced rCTS transmission scheme, fragmentation, and we assume that the stations in the low-rate group only participate in the competition through the backoff operation, which means that the stations in the high-rate group always work as relays not sources.

Let $S(t)$ be the random process representing the backoff stage of a station in the low-rate group and $C(t)$ be the random process representing the backoff counter value of a station in the low-rate group. So $C(t)$ at slot time t is a uniform random variable in the range of $[0, w_k - 1]$, where w_k is the backoff window of a station in the low-rate group at the kth backoff stage, i.e.,

$$w_k = \begin{cases} 2^k w_0, & 0 \le k \le K-1, \\ 2^K w_0, & K \le k \le L_{\mathrm{retry}} \end{cases} \tag{1}$$

where K is the maximum backoff stage and L_{retry} is the retry limit. Let $b_{k,l}$ be the steady state distribution of the Markov chain in Fig. 6, i.e.,

$$b_{k,l} = \lim_{t\to\infty} P\{S(t)=k, C(t)=l\}, \quad 0 \le k \le L_{\mathrm{retry}}, 0 \le l \le w_k - 1. \tag{2}$$

Let $P\{k,l|k_0,l_0\}$ be the state transition probability of the Markov chain shown in Fig. 6, i.e., $P\{k,l|k_0,l_0\} = P\{S(t+1)=k, C(t+1)=l|S(t)=k_0, C(t)=l_0\}$, then one can find

$$P\{k,l|k,l+1\} = 1-p_b, \ \ 0 \le w_k - 2, \tag{3}$$

$$P\{k,l|k,l\} = p_b, \ \ 1 \le l \le w_k - 1, \tag{4}$$

$$P\{k,l|k-1,0\} = p_c/w_k, \ \ 1 \le k \le L_{\mathrm{retry}}, \quad 0 \le l \le w_k - 1 \tag{5}$$

$$P\{0,l|k,0\} = (1-p_c)/w_0, \ \ 0 \le k \le L_{\mathrm{retry}}, \quad 0 \le l \le w_0 - 1, \tag{6}$$

$$P\{0,l|L_{\mathrm{retry}},0\} = 1/w_0, \ \ 0 \le l \le w_0 \tag{7}$$

where p_b and p_c denote the probability that a station in the low-rate group senses the channel busy and the probability that a transmitted frame of a station in the low-rate group collides, respectively. The probabilities p_b and p_c are obtained as

$$p_b = 1-(1-p_t)^{n-1}, \tag{8}$$

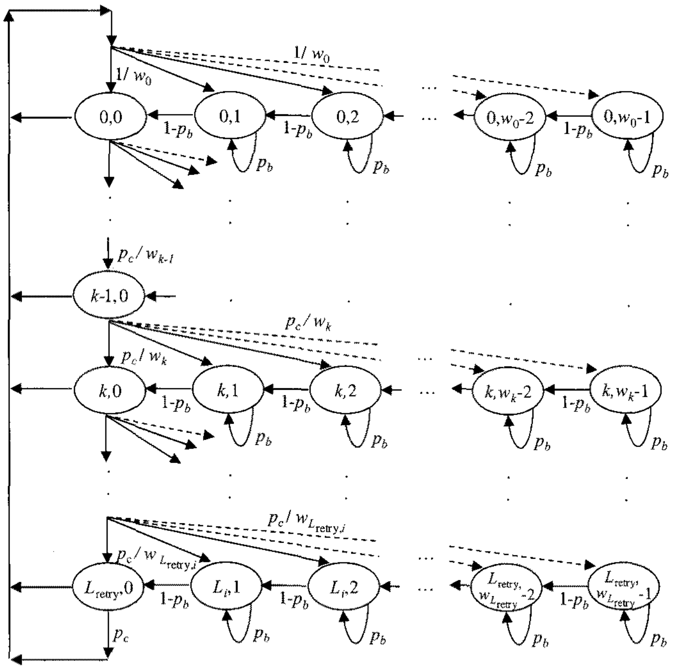

Fig. 6. The Markov chain model for AR-CMAC.

$$p_c = 1-(1-p_t)^{n-1} \tag{9}$$

where n is the total number of stations in the low-rate group and p_t is the probability that a station in the low-rate group transmits a frame during a slot time. Although the appearance of them is the same, their meanings are totally different. The probabilities p_t and the following relations can be derived from the steady state distribution $b_{k,l}$ as follows:

$$p_t = \sum_{k=0}^{L_{\text{retry}}} b_{k,0}, \tag{10}$$

$$b_{k,0} = p_c^k\, b_{0,0},\ \ 0 \le k \le L_{\text{retry}}, \tag{11}$$

$$b_{k,l} = \frac{w_k - l}{w_k}\frac{1}{1-p_b} b_{k,0},$$
$$0 \le k \le L_{\text{retry}},\ \ 1 \le l \le w_k - 1, \tag{12}$$

$$\sum_{k=0}^{L_{\text{retry}}} \sum_{l=0}^{w_k-1} b_{k,l} = 1, \tag{13}$$

$$b_{0,0} = \left[\sum_{k=0}^{L_{\text{retry}}} p_c^k \left(1+\frac{1}{1-p_b}\sum_{l=1}^{w_k-1}\frac{w_k-l}{w_k}\right)\right]^{-1}. \tag{14}$$

The probability p_s that a station in the low-rate group has successfully transmitted in a slot is given by

$$p_s = np_t(1-p_t)^{n-1}. \tag{15}$$

Next, when a station in the low-rate group has successfully transmitted in a slot, we need to find the probability of cooperative transmission, p^{CT}, and the probability of direct transmission, p^{DT}, which is determined from p_s^*. p_s^* denotes the probability that at least one rCTS is successfully transmitted during the interval of rCTSs. So p^{CT} and p^{DT} are

$$p^{CT} = p_s^* p_s, \tag{16}$$

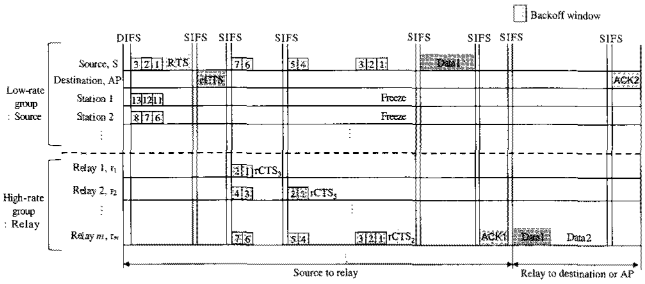

Fig. 7. The procedure of the simplified AR-CMAC.

$$p^{DT} = (1-p_s^*)p_s. \tag{17}$$

Note that p_s^* does not show any well-known distributions because a candidate active relay does not participate in the backoff competition again once its rCTS is transmitted to a source, which is different from the backoff operation of the legacy IEEE 802.11. So p_s^* is dependent not only on the number of candidate active relays, m, but also on the possible maximum number of rCTS transmissions, $n_r(= w_{\text{rCTS}})$. Let I_j be a Bernoulli random variable at the jth slot among $[1, w_{\text{rCTS}}]$. If the transmission of rCTS is successful at the jth slot, $I_j = 1$, otherwise, $I_j = 0$. We define the random variable R_J as

$$R_J = I_1 + I_2 + \cdots + I_J,\ \ J \in \{1, 2, \cdots, w_{\text{rCTS}}\}. \tag{18}$$

Then, p_s^* is defined as

$$p_s^* = P\{R_J \ge 1\} = 1 - P\{R_J = 0\}. \tag{19}$$

p_s^* can be obtained for different value of m:

$$p_s^* = \begin{cases} 1-0=1, & m=1,\\ 1-\dfrac{{}_{n_r}C_{1m}C_m}{(n_r)^m}, & m=2,\\ 1-\dfrac{{}_{n_r}C_{1m}C_m}{(n_r)^m}, & m=3,\\ 1-\dfrac{{}_{n_r}C_{1m}C_m + ({}_{n_r}C_{1m}C_{2(n_r-1)}C_{1(m-2)}C_{(m-2)}/2!)}{(n_r)^m}, & m=4. \end{cases} \tag{20}$$

As m becomes larger, the representation of p_s^* becomes more complex. We show the characteristics of p_s^* in Fig. 8. The probability that the channel is busy in a slot, p_{busy}, is given by

$$p_{\text{busy}} = 1-(1-p_t)^n. \tag{21}$$

Let p_{coll} denote the probability of collision. Then, we have

$$p_{\text{coll}} = 1 - \{(1-p_t)^n + np_t(1-p_t)^{n-1}\}. \tag{22}$$

Now, we can derive the saturation throughput of the simplified AR-CMAC. The saturation throughput can be obtained as:

$$T = \frac{8p^{CT}(S_{\text{source}} + S_{\text{relay}}) + 8p^{DT}S_{\text{source}}}{T_E + T_S + T_C} \tag{23}$$

where S_{source} is the MSDU size of a source in bytes, S_{relay} is the MSDU size of a relay in bytes, T_E is the mean slot time for the backoff operation of a source, T_C is the mean time when a

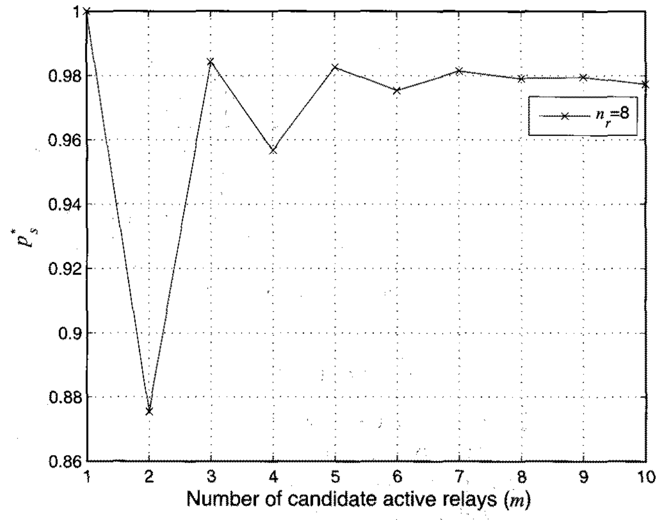

Fig. 8. The characteristics of p_s^* for varying m.

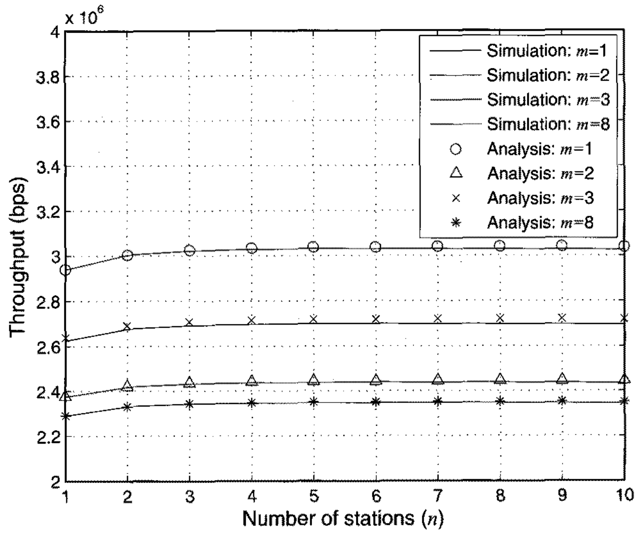

Fig. 9. Saturation throughput of the AR-CMAC for varying m.

collision occurs, and T_S the mean time to successfully transmit a frame. T_E, T_C, and T_S can be computed as follows:

$$T_E = (1 - p_{\text{busy}})T_{\text{slot}}, \tag{24}$$

$$T_C = p_{\text{coll}}T_{\text{coll}} = p_{\text{coll}}(T_{\text{DIFS}} + T_{\text{RTS}}), \tag{25}$$

$$T_S = p^{CT}T_{\text{frame}}^{CT} + p^{DT}T_{\text{frame}}^{DT} \tag{26}$$

where

$$\begin{aligned} T_{\text{frame}}^{CT} =& T_{\text{DIFS}} + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{cCTS}} + T_{\text{SIFS}} \\ &+ E[T_{\text{rCTS}}^{Tot}] + T_{\text{Data1}}^{CT} + T_{\text{SIFS}} + T_{\text{ACK1}} \\ &+ T_{\text{SIFS}} + T_{(\text{Data1+Data2})}^{CT} + T_{\text{SIFS}} + T_{\text{ACK2}}, \end{aligned} \tag{27}$$

$$\begin{aligned} T_{\text{frame}}^{DT} =& T_{\text{DIFS}} + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{cCTS}} + T_{\text{SIFS}} \\ &+ E[T_{\text{rCTS}}^{Tot}] + T_{\text{Data1}}^{DT} + T_{\text{SIFS}} + T_{\text{ACK1}}. \end{aligned} \tag{28}$$

T_{SIFS}, T_{DIFS}, and T_{slot} are the duration of short interframe space (SIFS), the duration of DIFS, and the duration of a slot time, respectively. Note that $E[T_{\text{rCTS}}^{\text{Tot}}]$ can be computed as

$$E[T_{\text{rCTS}}^{\text{Tot}}] = (T_{\text{DIFS}} + T_{\text{rCTS}})E[B] + (n_r - 1)T_{\text{slot}} \tag{29}$$

where B is the number of busy backoff slots during the possible maximum number of rCTS transmissions, n_r, which is obtained as

$$E[B] = \sum_{i=0}^{n_r} i\binom{n_r}{i}(p_b')^i(1-p_b')^{n_r-i}. \tag{30}$$

where the probability p_b' is the probability that the channel is busy at a slot due to the transmission of rCTSs, i.e.,

$$p_b' = 1 - \left(1 - \frac{1}{n_r}\right)^m. \tag{31}$$

In Fig. 9, we show the saturation throughput of the AR-CMAC, which is verified by simulation. The saturation throughput when $m = 1$ shows the best performance because the data of the source is always transmitted by the CT mode. In other cases, the CT mode is determined by the characteristic of p_s^*.

IV. PERFORMANCE EVALUATION

In order to evaluate performance, we consider an infrastructure network with an IEEE 802.11b/g AP supporting multi-rate WLANs, in which n stations are partitioned into various groups according to the channel condition since IEEE 802.11b can support four different transmission rates: 1, 2, 5.5, and 11 Mbps and IEEE 802.11g can support eight different transmission rates: 6, 9, 12, 18, 24, 36, 48, and 54 Mbps by link adaptation. The number of stations per group is fixed and ranges from 1 to 10. So the total number of stations in an IEEE 802.11b network environment ranges from 4 to 40 (Figs. 10, 11, and 13). Similarly, the total number of stations in an IEEE 802.11g network ranges from 8 to 40 as the number of stations per group varies from 1 to 5 (Fig. 15). Note that every station can be either a source or a relay. The effective transmission range of each group is decided to meet the sufficient SNR of the received signal for IEEE 802.11b environments [16] or for IEEE 802.11g environments [17], respectively. Simulations have been performed with the parameters described in Table 1 [13]. Moreover, for the 802.11g ERP-OFDM mode the PLCP protocol data unit (PPDU) format is considered, i.e., Service (16bits), Tail (6bits), Pad (variable by the PSDU size) [18] and a signal extension of 6 μs, a period of no transmission for the convolutional decode process to finish, is included [13].

In Fig. 10, the overall network throughputs of AR-CMAC, CoopMAC [11], and the legacy scheme in IEEE 802.11b environments are shown. The throughput of the legacy 802.11b is almost the same as the number of stations increases by the RTS/CTS scheme but throughput is low due to performance anomaly. CoopMAC is a table-based proactive protocol, so a proper relay is selected from its neighbor table and its performance depends on the accurate neighbor list of the table. In our simulation, the neighbor list is assumed to be ideally maintained and updated. CoopMAC shows better performance as the number of stations increases since cooperation overhead is relatively small by its table-based cooperation nature. Our AR-CMAC shows the improved performance by an appropri-

Table 1. Simulation parameters.

Parameters	802.11b	802.11g
MAC header+FCS	272 bits (CT) / 224bits (DT)	
MSDU (Default)	2304 byte	
RTS/CTS/ACK	352 bits / 304 bits / 304 bits	
cCTS/rCTS	304 bits / 320 bits	
$CW_{\max}$	1024 slots	
T_{SIFS}	10 μs	
T_{slot}	20 μs	9 μs
T_{DIFS}	50 μs	28 μs
$T_{\text{PLCP preamble}}$	144 μs	16 μs
$T_{\text{PLCP header}}$	48 μs	4 μs
$CW_{\min}$	32 slots	16 slots
w_{rCTS}	8 slots	8, 16, 32 slots
L_{retry}	6	7
Basic rate	1 Mbps	6 Mbps

Table 2. MSDU size (byte) and Initial CW size (slots).

	802.11b	DMA ($\text{CW}_{\min}=32$)	DICWA (MSDU=2304)
Setting I	Group1	MSDU=11×192	$\text{CW}_{\min}=32$
	Group2	MSDU=5.5×192	$\text{CW}_{\min}=64$
	Group3	MSDU=2×192	$\text{CW}_{\min}=128$
	Group4	MSDU=1×192	$\text{CW}_{\min}=256$
Setting II	Group1	MSDU=5.5×192	$\text{CW}_{\min}=128$
	Group2	MSDU=11×192	$\text{CW}_{\min}=32$
	Group3	MSDU=11×192	$\text{CW}_{\min}=32$
	Group4	MSDU=11×192	$\text{CW}_{\min}=32$

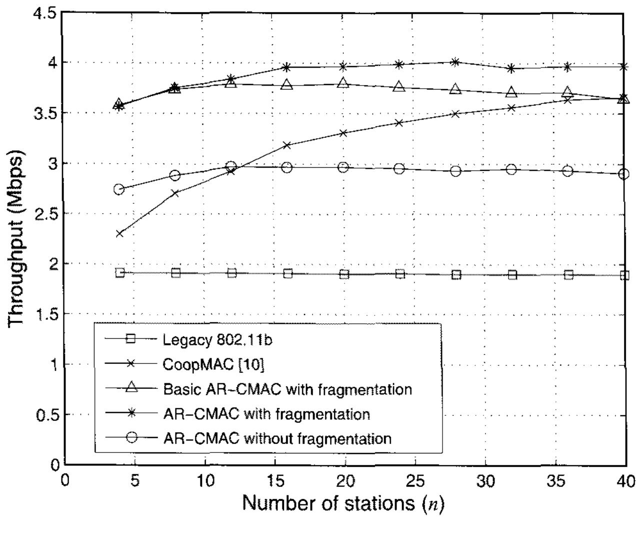

Fig. 10. Overall network throughput of AR-CMAC, CoopMAC, and the legacy scheme in IEEE 802.11b environments.

ate cooperation and improved channel utilization of higher-rate stations. AR-CMAC with fragmentation outperforms approximately 100% over the legacy 802.11b and approximately 10%–50% over CoopMAC.

The advanced rCTS transmission scheme of AR-CMAC as mentioned in subsection II-B reduces overhead by giving up

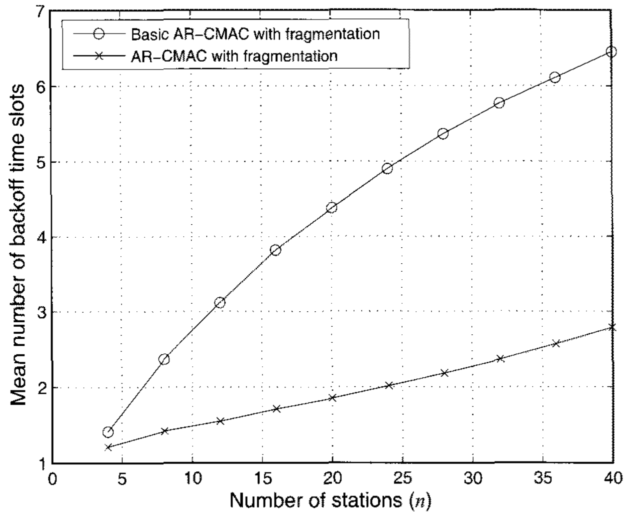

Fig. 11. Mean number of backoff time slots that rCTS frames are transmitted with and without rCTSs overhead reduction.

transmitting inferior rCTSs to the formerly transmitted superior rCTSs. In order to show the effectiveness of this reduction mechanism we compare our AR-CMAC with the basic AR-CMAC, which does not reduce cooperation overhead but allow the transmissions of all possible rCTSs until the backoff counter reaches $BO^{\text{Max}}_{\text{rCTS}}$. The throughput of the basic AR-CMAC with fragmentation decreases as the number of stations in the network increases since the overhead for cooperation becomes noticeable as shown in Fig. 11. We can observe that the number of transmitted rCTSs becomes greater as the number of stations in e network increases. Furthermore the mean number of transitted rCTSs of the basic AR-CMAC increases more drastically an that of AR-CMAC. Thus we can conclude AR-CMAC can eatly reduce the overhead. Besides, the throughput of AR-MAC with fragmentation is enhanced over 30% than that with-it fragmentation because of the improvement of the channel ilization by using lager MSDU size. So, the fragmentation is ficient for AR-CMAC when the MSDU size of a relay exceeds e maximum MSDU size.

In Fig. 12, we show the performance of the relay groups hen there are two nodes in the network: One node in the west-rate group (1 Mbps) and the other in a higher-rate group , 5.5, and 11 Mbps) in the IEEE 802.11b environments. The gend "transmission with cooperation" indicates the network roughput in which the nodes transmit by AR-CMAC and the T mode is used whenever the source node using 1 Mbps acsses channel. On the other hand, the legend "transmission without cooperation" represents the throughput in which the nodes always transmit directly without relay, i.e., the legacy IEEE 802.11b. As we mentioned, relaying through the highest-rate stations (source: 1, relay: 11) shows the best increase of throughput gain. We conclude the highest-rate group is the best relay group in the network model.

Moreover, we pay attention to the possibility of combining AR-CMAC with DMA or DICWA to further enhance performance. When AR-CMAC is combined with DMA or DICWA by parameter settings described in Table 2, we can observe more

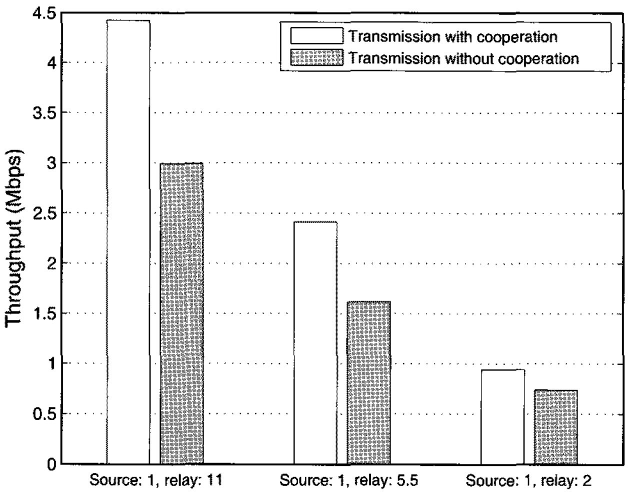

Fig. 12. Throughput comparison for relay groups.

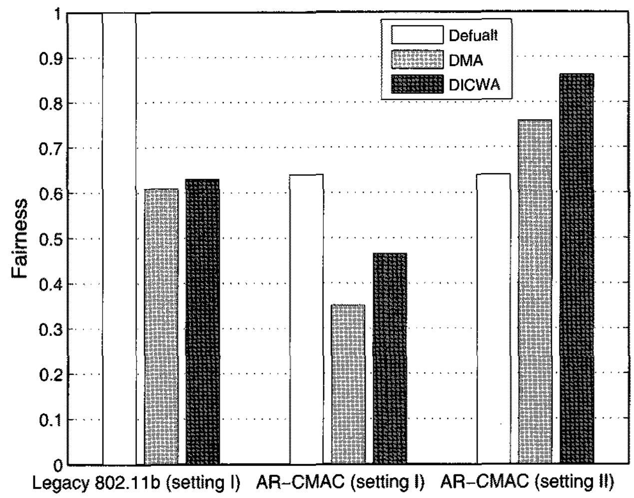

Fig. 14. Fairness of AR-CMAC and the legacy scheme in IEEE 802.11b environments.

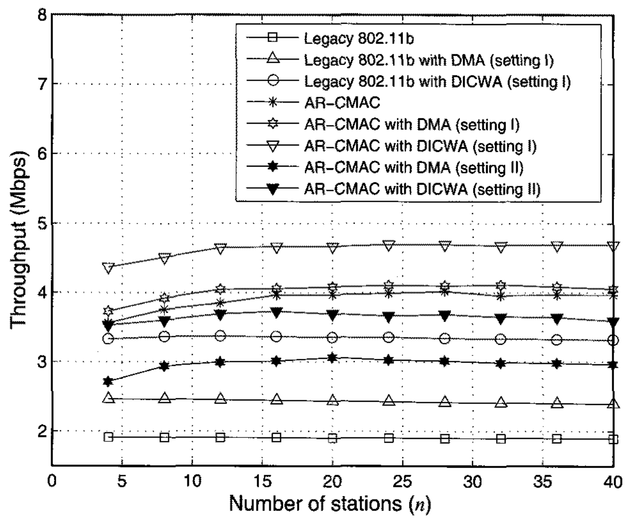

Fig. 13. Overall network throughput of AR-CMAC with DMA or DICWA in IEEE 802.11b environments.

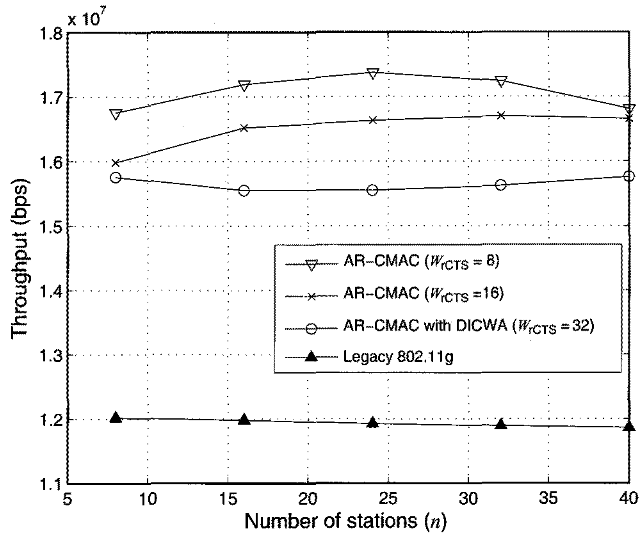

Fig. 15. Overall network throughput of AR-CMAC and the legacy scheme in IEEE 802.11g environments.

throughput increase than AR-CMAC only as in Fig. 13 (setting I). For comparison, we show the throughput of DMA and DICWA applied to the legacy 802.11b and confirm that both can be alternatives to mitigate performance anomaly. Remarkably, AR-CMAC with DICWA (setting I) shows the best performance and throughput is improved approximately 130% than that of the legacy 802.11b.

The enhancement of throughput may be achieved at the cost of fairness because DMA gives more channel occupancy time to higher-rate stations and DICWA gives more channel access chance to higher-rate stations in addition to compensations for relaying, i.e., extra transmission chances for relay. The throughput fairness by Jain's index [19] among four groups in IEEE 802.11b environments is shown in Fig. 14 when the number of stations is 24. By the characteristics of CSMA/CA in legacy 802.11b, i.e., fair channel access chances and fair long-term throughput among all stations, fairness index is one. We can observe that there is a trade-off between throughput and fairness. Note that DMA and DICWA can solve the performance anomaly by the low-rate stations but require the sacrifice of low-rate stations. The benefits of cooperation using AR-CMAC CT mode are throughput improvement of lower-rate stations as well as more transmission chances of higher-rate stations as shown in Fig. 9. Another setting of DMA and DICWA, e.g., setting II in Table 2, can be provided to enhance fairness if it is required.

Finally, we show the overall network throughput of AR-CMAC and the legacy 802.11g in IEEE 802.11g environments in Fig. 15. In this case, the mean number of transmitted rCTSs may increase because there are more groups than those in IEEE 802.11b environments. When the number of stations is large and w_{rCTS} is 8, overall network throughput slightly deceases. In the case of $w_{\mathrm{rCTS}} = 16$, the throughput curve looks flat as the number of stations becomes larger. However, the overall network throughput decreases when w_{rCTS} is 16 or 32 due to the cooperation overhead of large backoff slots. Note that the throughput of AR-CMAC is enhanced approximately 30%–50% than that of the legacy IEEE 802.11g.

V. CONCLUSION

In this paper, we have proposed a new cooperative MAC protocol for multi-rate WLANs: AR-CMAC. Our protocol is simple because the handshaking procedure for cooperation between fully distributed stations is followed by the legacy BEB algorithm. Moreover, AR-CMAC can be employed to any multi-rate WLANs based on CSMA/CA with RTS/CTS, e.g., IEEE 802.11a/b/g. In AR-CMAC, the role of high-rate relay stations is shown to be important. High-rate relay stations help to reduce the time required to send the data of low-rate source stations as well as their own data by cooperation. We have developed analytical model using an embedded Markov chain model for AR-CMAC and analyze the characteristics of proposed relay selection scheme. Through analysis and simulations, we have verified performance enhancement of AR-CMAC compared to the legacy IEEE 802.11b/g and CoopMAC. AR-CMAC shows better throughput performance than the legacy schemes. Additionally we further enhance the throughput of AR-CMAC by combining DMA and DICWA at the cost of fairness, which is tunable by appropriate parameter settings. Simulation results indicate that AR-CMAC with DICWA shows the best performance in terms of throughput.

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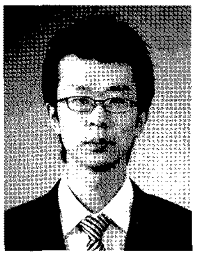

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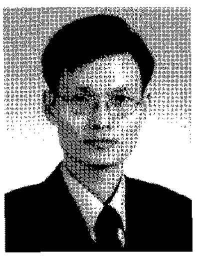

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