

Performance Evaluation of the Reliable Cooperative MAC Protocol in Ad Hoc Networks

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Abstract—A new reliable cooperative MAC protocol called RCO-MAC is proposed, and the protocol's performance is evaluated with numerical analysis and computer simulation. The key concept for this RCO-MAC protocol is to give the responsibility of the error recovery by retransmission for a frame to the node that transmits the frame. The system throughput is used as a performance metric. According to numerical results, it is shown that the scheme proposed in this paper provides over 20% more system throughput than the rDCF scheme.

Index Terms—Cooperative MAC, WLAN, CRTS, helper node, rDCF

I. INTRODUCTION

When mobile stations are located around a cell boundary or two mobile nodes in an ad hoc network [1] are located at a good distance away or under a fading environment, severe transmission errors are inevitable even in the 4G mobile communication system. Although repeater systems have been used in mobile communication systems until now in order to improve the transmission quality around cell boundaries, these repeater systems cannot be used to improve the transmission quality in ad hoc networks, where the network topology is variable due to terminal mobility.

Nowadays, cooperative communication [2] has been introduced to improve the transmission quality with the help of intermediate nodes located between the source node and the destination node. Most of researches have been carried out based on IEEE 802.11 WLAN protocol [3] because this WLAN protocol provides good system throughput over one-hop wireless network environment. The pioneer research for performance analysis of this WLAN protocol has been carried by Bianchi [4] and later the throughput and delay analysis for IEEE 802.11e protocol that provides QoS service over the traditional WLAN protocol has been presented by Tantra [5]. Up to now, most of researches on performance analysis for various cooperative MAC protocols following after Bianchi have been carried out based on [4]. The receiver-based auto rate (RBAR) [6] scheme has been proposed, which describes the procedure and the related frame header format for accommodating a link adaptation scheme in the wireless LAN system. Many studies on cooperative communication have been conducted. First of all, the CMAC scheme that

supports cooperative communication with the RBAR scheme and with a minimum change from the distributed coordination function (DCF) mechanism has been proposed in [7]. This work describes the retransmission scheme between two nodes when transmission errors take place and the FCMAC scheme that combines the CMAC scheme with a channel coding scheme. The relay DCF (rDCF) scheme, which is an enhanced version of the DCF scheme for cooperative communication, has been proposed in [8]. In this rDCF scheme, the procedure for deciding helper nodes, modified control frames (RRTS1, RRTS2, and RCTS frames), and the frame transmission procedure between the source, destination, and helper nodes are described in detail. The CoopMAC scheme has been proposed in [9]. It is remarkable that this scheme suggested a mathematical guideline for clearly deciding helper nodes. In order to get a diversity gain at the channel contention stage, the CODE scheme [10] changed the traditional triangular handshake for cooperative communications into the diamond handshake. Putting these previous studies together, we realized that those studies did not consider transmission errors due to bad wireless channels and that these schemes are compared only with the RBAR scheme, which is only the DCF scheme rather than a cooperative communication scheme.

In this paper, we present the performance evaluation of a new cooperative MAC protocol called the reliable cooperative MAC (RCO-MAC) protocol [11] that provides reliable and high system throughput over a bad wireless channel, and evaluate its performance with mathematical analysis and computer simulations. In this paper, the range where frame transmission errors can take place has been extended to the whole gamut of frame transmissions. Therefore, frame transmission errors can happen on any frame transmission including the CRTS frame. A detailed explanation of the proposed RCO-MAC is presented in Section II, and system modeling and performance analysis are provided in Section III. Then, the numerical results from analysis and simulation are provided in Section IV, and finally this paper is concluded in Section V.

II. RCO-MAC PROTOCOL

The RCO-MAC protocol proposed in this paper for cooperative communications is based on the DCF scheme of IEEE

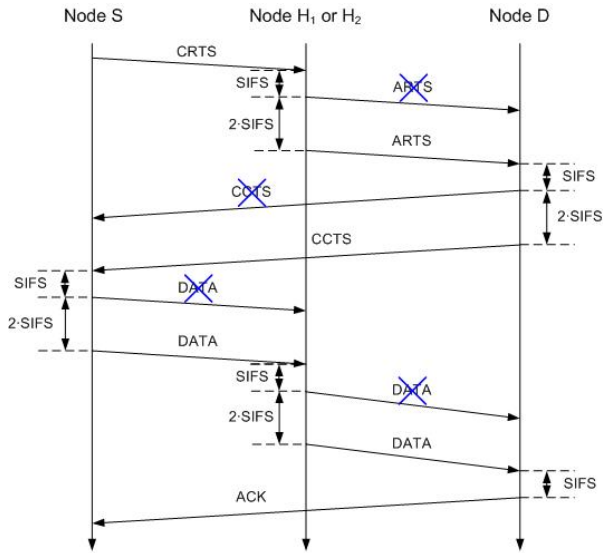


Fig. 1. Frame exchange chart at the RCO-MAC protocol

wireless LAN [3]. Over a bad wireless channel, basically it is favorable that the node transmitting a frame is responsible for successful transmission for this frame. However, in the rDCF [8] scheme, only source nodes are responsible for successful transmission of any frame. For clarification, let's consider a simple cooperative network group consisting of a source node, a destination node, and a helper node. According to the rDCF scheme, for the first time the sender node transmits an RRTS1 (relay RTS) frame to the helper node based on the CSMA/CA channel contention algorithm. Then, the helper node sends the RRTS2 frame to the destination node SIFS period after the node receives the RRTS1 frame successfully. And then, the destination node sends the CCTS frame to the sender node SIFS period after the RRTS2 frame is received successfully. If the helper node fails to transmit the RRTS2 frame to the destination node successfully, then the source node cannot get the CCTS frame within a pre-defined period. At that time, the source node notices the need of retransmission by the timeout of the retransmission timer in itself and retransmits the RRTS1 frame, and thus, the whole transmission procedure begins from the start. Since the only node responsible for successful transmissions is the source node, this scheme takes a long time for error recovery. On the other hand, in the RCO-MAC protocol the helper node that transmitted the RRTS2 frame to the destination node is in charge of the successful transmission of this frame. Therefore, the helper node can retransmit the RRTS2 frame when the node does not sense any signal within a pre-defined duration.

The overall operating procedure for the RCO-MAC is presented in Fig. 1. In this paper, how to choose appropriate helper nodes is not described but each node is assumed to know its helper node in advance, because this RCO-MAC scheme is assumed to use the same helper node selection scheme as the rDCF or CoopMAC scheme. When a source node (Node S in Fig. 1) has a frame to transmit, the

node should start the transmission procedure based on the CSMA/CA protocol. So, the node initializes the contention window (CW) first and then sends a CRTS frame to the helper node (Node H in Fig. 1) at the basic rate. In addition, the source node triggers timer 1, whose value will be described later, for an error recovery by retransmission. If the node receives the CCTS (cooperative CTS) frame before timer 1 expires, then the node sends the DATA frame to the helper node at the supportable maximum transmission rate based on the measured SNR value. For error recovery with retransmission, every node handles a new variable i , the number of transmissions for the frame until now and this variable should be equal to or less than n , the maximum number of transmissions allowed for each node. The source node handles two additional timers, timer 2 and timer 3. Timer 2 is for error recovery of the DATA frame. Thus, if the node does not sense the DATA frame transmitted by the helper node to the destination node during two SIFSs, the node retransmits the DATA frame again. If this node does not receive the ACK frame before timer 3 expires, then the node returns to the start by doubling the contention window. Each timer described above is set as the following values, where the frame name (ex. CCTS) means the transmission time for that frame.

- Timer 1 : $2 \times \text{SIFS} + \text{ARTS} + (\text{ARTS} + 2 \times \text{SIFS}) \times (n-1) + \text{CCTS} + (\text{CCTS} + 2 \times \text{SIFS}) \times (n-1)$
- Timer 2 : $2 \times \text{SIFS}$
- Timer 3 : $2 \times \text{SIFS} + \text{DATA} + (\text{DATA} + 2 \times \text{SIFS}) \times (n-1) + \text{ACK}$

If the helper node receives the CRTS frame from the source node, the helper node sends the ARTS (acknowledge RTS) frame to the destination node (Node D in Fig. 1) and triggers timer 2 for error recovery. If the helper node senses the CCTS frame transmitted by the destination node before the timer expires, the helper node has finished its role successfully. Otherwise, the helper node retransmits the ARTS frame for error recovery. If the helper node receives the DATA frame from the source node, this node forwards the frame to the destination node. In this case, the error recovery procedure for this frame is the same as one for the ARTS frame.

If the destination node receives the ARTS frame from the helper node, the destination node transmits the CCTS frame directly to the source node at the basic rate. The node's error recovery procedure is the same as one described above for the helper node. If the frame received by the destination node is the DATA frame, then the node sends back the ACK frame directly to the source node at the basic rate. In this case, however, the node skips the error recovery procedure even when this ACK frame is in error. Among three timers described above, timer 1 and timer 2 will be needed in the rDCF scheme, too. However, the values for the timers in the RCO-MAC is greater than one in the rDCF scheme because of the different retransmission function carried out by each node.

III. PERFORMANCE EVALUATION

Let's define several system variables required for performance analysis.

In the calculation of those steady-state probabilities, the CRTS frame transmission probability τ and the transmission failure probability for CRTS frame due to collision p_c should be replaced with

$$\tau = \sum_{i=0}^r \alpha_{i00} = \frac{1 - (p_f + B)^{r+1}}{1 - (p_f + B)} \cdot \alpha_{000} \quad (8)$$

$$p_c = 1 - (1 - \tau)^{K-1} \quad (9)$$

For performance analysis, the system throughput in bps is considered and it is defined as the ratio of the total amount of data transmitted successfully to the simulation duration. In order to derive the numerical formula for system throughput, two types of average delays should be calculated in advance. The first one is D_S the average time delay from the transmission of the ARTS frame to the successful reception of the ACK frame, and the next one is D_E the average time delay from the transmission of the ARTS frame to the complete transmission failure after n -th retransmission of ARTS, CCTS or DATA frame or after ACK frame transmission. In order to calculate D_S , the average time delays for the successful frame transmission at each phase, D_S^i , $i = 1, 2, \dots, 5$, should be derived first and thus are given by

$$\begin{aligned} D_S^1 &\equiv \sum_{i=1}^n \{(\text{ARTS} + \text{SIFS} + (i-1)(\text{ARTS} + 2\text{SIFS}))\} \\ &\quad \cdot p_m^{i-1} (1 - p_m) \\ D_S^2 &\equiv \sum_{i=1}^n \{(\text{CCTS} + \text{SIFS} + (i-1)(\text{CCTS} + 2\text{SIFS}))\} \\ &\quad \cdot p_m^{i-1} (1 - p_m) \\ D_S^3 &\equiv \sum_{i=1}^n \{(\text{DATA} + \text{SIFS} + (i-1)(\text{DATA} + 2\text{SIFS}))\} \\ &\quad \cdot p_d^{i-1} (1 - p_d) \\ D_S^4 &\equiv \sum_{i=1}^n \{(\text{DATA} + \text{SIFS} + (i-1)(\text{DATA} + 2\text{SIFS}))\} \\ &\quad \cdot p_d^{i-1} (1 - p_d) \\ D_S^5 &\equiv \text{ACK} \end{aligned}$$

where those frames' name (ex. ARTS) means the transmission time for each frame. Then, the average time delay from the ARTS transmission to successful reception of the ACK frame can be derived as

$$D_S = D_S^1 + D_S^2 + D_S^3 + D_S^4 + D_S^5. \quad (10)$$

In similar way, the average time delays until transmission failure at each phase, D_E^i , $i = 1, 2, \dots, 5$, are given by

$$\begin{aligned} D_E^1 &\equiv \text{ARTS} + \text{SIFS} + (n-1)(\text{ARTS} + 2\text{SIFS}) \\ D_E^2 &\equiv \text{CCTS} + \text{SIFS} + (n-1)(\text{CCTS} + 2\text{SIFS}) \\ D_E^3 &\equiv \text{DATA} + \text{SIFS} + (n-1)(\text{DATA} + 2\text{SIFS}) \\ D_E^4 &\equiv \text{DATA} + \text{SIFS} + (n-1)(\text{DATA} + 2\text{SIFS}) \\ D_E^5 &\equiv \text{ACK}. \end{aligned}$$

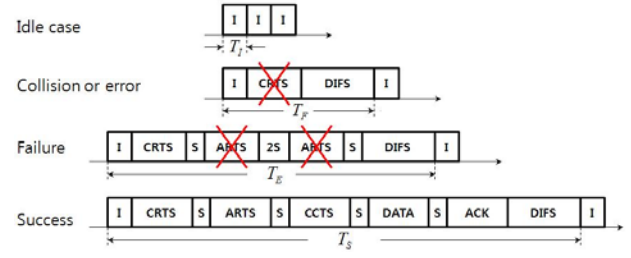


Fig. 3. Examples of various time slots

Then, the average time delay from ARTS frame to complete transmission failure can be derived as

$$\begin{aligned} D_E &= D_E^1 \cdot \frac{p_m^n}{P_t} + (D_S^1 + D_E^2)(1 - p_m^n) \cdot \frac{p_m^n}{P_t} \\ &\quad + (D_S^1 + D_S^2 + D_E^3)(1 - p_m^n)^2 \cdot \frac{p_d^n}{P_t} \\ &\quad + (D_S^1 + D_S^2 + D_S^3 + D_E^4)(1 - p_m^n)^2(1 - p_d^n) \cdot \frac{p_d^n}{P_t} \\ &\quad + (D_S^1 + D_S^2 + D_S^3 + D_S^4 + D_E^5)(1 - p_m^n)^2 \\ &\quad \cdot (1 - p_d^n)^2 \cdot \frac{p_m}{P_t} \end{aligned} \quad (11)$$

where

$$\begin{aligned} P_t &= p_m^n + (1 - p_m^n)p_m^n + (1 - p_m^n)^2 p_d^n + (1 - p_m^n)^2 \\ &\quad \cdot (1 - p_d^n)p_d^n + (1 - p_m^n)^2(1 - p_d^n)^2 p_m. \end{aligned}$$

The probability that there is at least one CRTS frame transmitted by K mobile users in the considered time duration, P_{tr} , and another probability that the transmitted CRTS frame is successfully received to the helper node without collision and transmission error, P_s , are calculated as

$$P_{tr} = 1 - (1 - \tau)^K \quad (12)$$

$$P_s = \frac{K\tau(1 - \tau)^{K-1}}{P_{tr}}(1 - p_m). \quad (13)$$

Futhermore, the probability P_a that any transmission error does not take place during the period from ARTS frame to ACK frame transmission can be derived as

$$P_a = (1 - p_m^n)^2(1 - p_d^n)^2(1 - p_m). \quad (14)$$

According to this protocol, there are four different types of slot time which means the variable time interval between two consecutive backoff time counter decrements. First, when there is no transmission on the channel, the slot time means the slot duration $T_I = \sigma$. Second, when the transmission of CRTS frame results in failure due to collision or bad wireless channel, the slot time becomes T_F . Third, when the source node does not receive the ACK frame even after the successful transmission of the CRTS frame, the slot time becomes T_E . Lastly, if the total transmission scenario is successful, then this slot time is T_S . All of them are exemplified clearly in Fig.3

when $n = 2$ and are indicated as

$$\begin{aligned} T_I &= \sigma \\ T_F &= \text{CRTS} + \text{DIFS} + \sigma \\ T_E &= \text{CRTS} + \text{SIFS} + D_E + \text{DIFS} + \sigma \\ T_S &= \text{CRTS} + \text{SIFS} + D_S + \text{DIFS} + \sigma. \end{aligned}$$

Then, the average size of the time slot can be shown as

$$E[S] = (1 - P_{tr})T_I + P_s P_{tr} P_a T_S + P_s P_{tr} (1 - P_a) T_E + P_{tr} (1 - P_s) T_F. \quad (15)$$

Since the system throughput can be calculated as the ratio of the DATA frame transmission time to the average time slot, it is given by

$$S = \frac{P_s P_{tr} P_a E[P]}{E[S]} \cdot R_{max} \quad [\text{bps}] \quad (16)$$

where R_{max} is the maximum transmission rate and $E[P]$ is the transmission time for the DATA frame.

IV. NUMERICAL RESULTS

For the performance evaluation of this RCO-MAC protocol, the mathematical analysis and computer simulations have been conducted. The simulation code was programmed with a C language based on SMPL library [12]. The system parameters used in the performance evaluation are described in Table I. All control frames are assumed to be transmitted at the basic rate and DATA frames are assumed to be transmitted always at R_{max} . The reason for this DATA frame transmission rate is described in the following sentence. It is assumed here that the transmission path between the helper nodes and source or destination nodes can provide 11 Mbps and that control and DATA frame transmission error probabilities by bad wireless channel are the same for simplicity. In this table, R_{sh} means the transmission rate between a source node and a helper 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	32 slots
ACK length	304 bits	CWmax	1024 slots
DATA length	1024 bytes	R_{sh}, R_{hd}	11 Mbps
Slot size (σ)	20 μ s	Basic rate	1 Mbps
n	variable	$p_m(p_d)$	variable
R_{max}	11 Mbps		

The system throughputs by analysis and simulation for the RCO-MAC with $n = 3$ are presented and compared in Fig. 4. These numerical results are computed as functions of various frame transmission errors ($p_m = p_d$) and the different number of source nodes. In this figure, analysed results are shown in various types of lines and simulated results are shown in various types of points. This figure shows us two facts that system throughputs computed at lower frame transmission error provides better system performance than one at higher frame transmission error and that, as the number

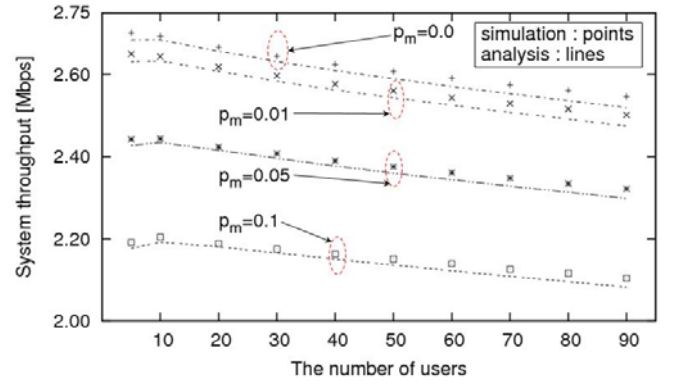


Fig. 4. System throughputs by analysis and simulation($n = 3$)

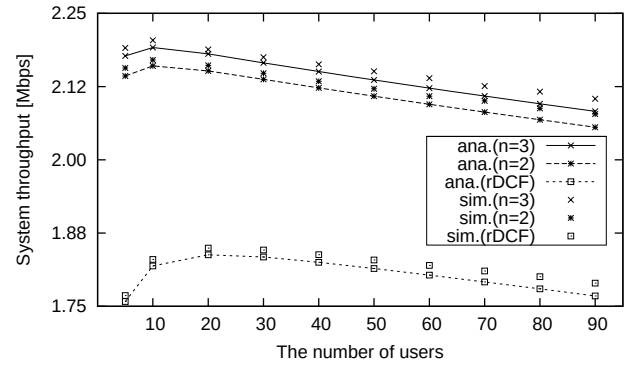


Fig. 5. Comparison of system throughput performance($p_m = 0.1$)

of source nodes increases, the overall system throughputs tend to decrease. The one is because increased error probability causes lots of retransmission and thus decreased number of successful transmissions, and the other is because increased number of source nodes means increased CRTS frame collision probability. It is shown from this figure that analytic results coincide with simulated results over reasonable system environments.

The system throughputs by analysis and simulation for the RCO-MAC protocol with various n and rDCF scheme are presented and compared in Fig. 5. These numerical results are calculated for frame transmission error probability 0.1. According to this figure, the RCO-MAC protocol with $n = 3$ provides over 20% more system throughput than the rDCF scheme. Although the RCO-MAC protocol may provide similar system throughput with the rDCF when frame transmission error is very low, it is clear from this figure that this RCO-MAC protocol provides much better system throughput performance than the rDCF protocol at mobile ad hoc networks.

V. CONCLUSION

In this paper, a new reliable cooperative MAC protocol called RCO-MAC is proposed and its performance is evaluated. Performance evaluation has been carried in two ways, mathematical analysis and computer simulation. According to

numerical results, the RCO-MAC protocol provides over 20% higher system throughput than the rDCF. For further study, we are planning to design a new cooperative MAC protocol with cross-layer design considering the MIMO and smart antenna physical layer technologies.

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