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A Robust and Cooperative MAC Protocol for IEEE 802.11a Wireless Networks

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Abstract In wireless networks, it is well known that the interference of hidden nodes can interrupt frame receptions. Although several solutions have been proposed to alleviate the problem of DATA corruptions at receivers, control frame corruptions at transmitters have not been considered yet. In this paper, we propose an enhanced MAC protocol, called Robust and Cooperative Medium Access Control (RCMAC), to improve the network throughput and fairness by reducing control frame losses at transmitters. RCMAC uses a relay mechanism to allow transmitters of long distance links to receive control frames more robustly by relaying control frames via relay nodes. Furthermore, RCMAC improves the network throughput through fast two-hop DATA transmissions via relay nodes. Our extensive simulation results show that RCMAC has better performance than existing well-known MAC protocols.

Keywords Carrier sensing range · Interference · Relay mechanism · Medium access control

1 Introduction

Thanks to the low cost and multi-rate capability, IEEE 802.11 WLANs are widely used in these days. One of the important issues in IEEE 802.11 wireless networks is to increase network throughput under limited bandwidth. However, the hidden node problem that can

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occur in IEEE 802.11 wireless networks is one of the main problems that degrade the network throughput.

The IEEE 802.11 standard [5] defines the distributed coordination function (DCF) that is based on the carrier sense multiple access with collision avoidance (CSMA/CA). In DCF, the Request-To-Send (RTS)/Clear-To-Send (CTS) handshake (or four-way handshake) has been designed to handle the hidden node problem. Four-way handshake works well under the condition that all hidden nodes are within the transmission range of a receiver. However, Xu et al. [18] revealed that the assumption cannot be held since receivers need much higher reception power than interference power to successfully receive frames. This means that interference by hidden nodes outside of the transmission range of the receiver may disrupt frames.

Several schemes [18,9,20,11,15,17,3,8] have been proposed to alleviate frame losses in IEEE 802.11 based wireless network, which can be classified into single channel approach and multi channel approach. Xu et al. [18] proposed a MAC scheme called Conservative CTS Reply (CCR) to reduce frame losses, which is the first article to deal with the problem in single channel [18,20,11,15]. In the scheme, when receiving RTS, the receiver returns CTS only if the received signal strength of the RTS is higher than a certain threshold. However, CCR has lower network connectivity due to reduced effective transmission ranges. Shan et al. [15] proposed the probabilistic CTS reply (PCR) scheme to handle frame losses as well as to overcome low network connectivity in CCR. In PCR, the receiver sends CTS as a response with probability $1 - P$, where P denotes the interference probability at the receiver. However, since PCR does not consider interference at the transmitter, transmitter side frame losses (e.g., CTS and ACK losses) still remain. Another single channel approach, opportunistic retransmission schemes, has been proposed to alleviate frame losses [20,11]. These opportunistic retransmission schemes are based on the idea that intermediate nodes that are closer to the receiver than the transmitter opportunistically participate in the retransmission phase if they overhear DATA from the transmitter and detect that the receiver fails to receive DATA. However, retransmission schemes do not focus on the effect of transmitter side frame losses.

Several multi-channel protocols [9,17,3,8] have been designed to handle frame losses caused by interference. Leng et al. [9] proposed an enhanced IEEE 802.11 scheme that utilizes dual busy tones during the transmission phase of DATA. The transmitter and receiver use busy tones that are sent with sufficient power to cover the entire interference range until the reception time of ACK and DATA respectively. Similarly, the receiver-initiated busy tone multiple access protocol [17] and dual busy tone multiple access (DBTMA) [3] use out-of-band busy tones for signaling the ongoing transmission to handle the same problem. Also, in power control interference avoidance (PCIA) [8], control channel is separated from data channel and different transmit power is used in the transmissions of control frames and data frames to avoid interference induced frame losses as well as to retain a high level of power efficiency. These multi-channel approaches can also eliminate the transmitter side frame losses in IEEE 802.11a wireless networks, but it needs additional hardware for supporting dual busy tones or multi channel.

Those existing approaches focused on the impact of receiver side frame losses (i.e., DATA) on network performance. However, we found that control frame losses at transmitters have a big impact on the throughput of WLANs. Particularly, the loss of CTS frames waste the wireless medium during the time duration set by NAV, and the loss of ACK frames causes unnecessary retransmissions. Although the IEEE 802.11 standard defines extended interframe space (EIFS), which is a special IFS used by a node that has sensed a frame error, to prevent transmitter side frame losses, it is effective only if the carrier sensing range is large enough to cover the entire interference range at the transmitter. The losses of CTS and ACK still remain in 802.11a wireless networks due to the unique feature of 802.11a PHY where the carrier sensing range is the same as the transmission range [13]. Although some existing approaches [18,9,17,3,8] can alleviate transmitter side frame losses in IEEE 802.11a networks, they have their own limitations.

In this paper, we propose an efficient MAC protocol, called *Robust and Cooperative MAC* (RCMAC) for IEEE 802.11a wireless networks. We propose a relay mechanism inspired by relay MAC protocols [21,23,10] that use fast two hop transmissions via an intermediate node to improve the overall network throughput by reducing the transmission time. However, unlike these protocols, we exploit two hop relay transmissions not only to reduce transmission time but also to alleviate control frame losses caused by interferences. Through our extensive simulations, we found that RCMAC reduces control frame losses, improves the system throughput, and achieves enhanced link fairness compared with existing protocols.

The rest of this paper is organized as follows. Section 2 describes background. In Sect. 3, we explain the impact of interference on the performance of IEEE 802.11a wireless networks. Section 4 describes the detailed operation of RCMAC. Section 5 evaluates the performance of RCMAC via extensive simulations. Finally, we conclude this paper in Sect. 6.

2 Background

In previous studies, the concept of using relay nodes to improve the throughput of multi-rate WLANs has received much attention [21,23,10]. The key motivation of the studies is that multi-hop relaying at the MAC layer may support higher data rates than a single hop transmission. Although the protocols have their own unique features, their overall operations are very similar to each other. In the following, we describe the operation of the relay-enabled DCF (rDCF) protocol [21], which is one of the representative frame-relaying protocols.

In rDCF, each node promiscuously listens to all ongoing RTS and CTS frames to know the channel condition between a transmitter and receiver. Each node senses the signal strength of RTS or CTS to measure the channel quality between the transmitter or the receiver and itself. If a node determines that data frames can be transmitted faster with MAC layer relay, it adds the addresses of the transmitter and receiver in the list of expected neighbors. The list is periodically advertised to one-hop neighbors and each node maintains a relay table based on the advertisements.

When a transmitter tries to transmit a frame, it performs triangular handshake as shown in Fig. 1a, if there is a possible relay node in the relay table. First, S (transmitter) sends relay RTS1 (RRTS1) to R to make an agreement on relay transmissions. Upon receiving RRTS1, R sends relay RTS2 (RRTS2) to D. After overhearing RRTS1 and receiving RRTS2, D decides whether relaying DATA or not. Then, D notifies the decision to S via relay CTS (RCTS), which includes the transmission rate information from S to R (R_{SR}) and from R to D (R_{RD}). Finally, S receives RCTS from D and knows how to transmit DATA by relay or direct transmissions.

Figure 1b shows the DATA transmission procedure when relay transmission is used. First, S transmits DATA with the transmission rate of R_{SR}. If R receives the DATA frame

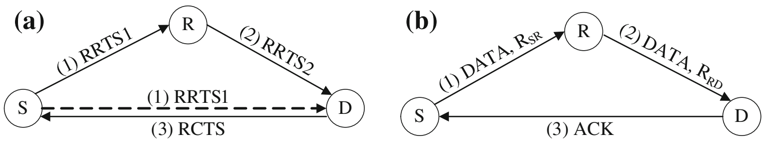

Fig. 1 rDCF operation: (**a**) *triangular* handshake, (**b**) DATA transmission via a relay node

successfully, it relays the frame to D with the transmission rate of R_{RD} after a short interframe space (SIFS) without any further channel contention. When D receives the DATA frame, it sends ACK to S as a response after a SIFS.

Unlike these relaying protocols [21,23,10] that focus on faster frame transmissions, we exploit two hop relay transmissions not only to reduce transmission time but also to alleviate transmitter side control frame losses caused by interferences.

3 Impact of Interference on IEEE 802.11a Wireless Networks

In the section, we explain transmitter side control frame losses (e.g., CTS and ACK) which is a unique feature occurred only in IEEE 802.11a systems, and then identify how much transmitter side frame losses degrades network performance via simulations.

3.1 Radio Ranges in 802.11

There are four different radio ranges in IEEE 802.11: transmission range, NAV set range, interference range, and carrier sensing range. Transmission range is the range within which a node can receive and decode frames successfully if there are no interfering nodes. Generally, the transmission range decreases as the transmission rate increases. NAV set range (d_{nav}) is the range within which RTS or CTS can be decoded. In DCF, when neighbors of a transmitter and receiver overhear RTS or CTS, they set NAVs and cannot transmit their frames during the transmission phase of subsequent DATA and ACK. Since RTS and CTS are transmitted at a base rate (e.g., 6 Mbps in IEEE 802.11a), the NAV set range is the same as the transmission range with the base rate.

Interference range (d_i) is the range within which the reception of frames at a node can be interrupted by neighbors. The range depends on the distance between the transmitter and receiver and the used transmission rate. Particularly, it can be expressed by

$$d_i = \sqrt[4]{SINR_x} \times d \tag{1}$$

where $SINR_x$ is the required signal to interference plus noise ratio (SINR) value for successfully receiving frames with rate x and d is the distance between a transmitter and receiver [13]. Table 1 shows SINR and receiver sensitivity values for data rates from 6 to 54 Mbps. In order to receive a frame with a certain rate successfully, a receiver should satisfy the

Table 1 SINR and receiver sensitivity according to transmission rates [19]

Transmission rates (Mbps)	SINR (dB)	Receiver sensitivity (dBm)
54	24.56	−65
48	24.05	−66
36	18.80	−70
24	17.04	−74
18	10.79	−77
12	9.03	−79
9	7.78	−81
6	6.02	−82

following two conditions: (i) the received signal strength is higher than the receiver sensitivity at a certain rate in Table 1, and (ii) the calculated SINR ($SINR_{RX}$) is higher than SINR at a certain rate in Table 1, which is expressed by

$$SINR_{RX} = \frac{P_r}{\Sigma_i P_i} \geq SINR_x \tag{2}$$

where P_r is the received signal strength from the intended transmitter, and P_i is the received signal strength from interferer i.

Carrier sensing range is the range within which the signal of a frame can be sensed as busy during the frame transmission. According to the IEEE 802.11 standard [5], the Clear Channel Assessment (CCA) that is used for determining the channel status (i.e., busy or idle) is executed by carrier detection or energy detection at the PHY layer. Nodes try to transmit frames only if the current channel status is idle. Thus, nodes inside the carrier sensing range of a node cannot interfere with the frame reception of the node.

3.2 Interference-Induced Control Frame Loss in 802.11a

Now, we consider the effect of interference on control frame (e.g., RTS, CTS, and ACK) reception in 802.11a. Since the control frames are transmitted with 6 Mbps, the interference range for control frames ($d_{i,ctr}$) is $\sqrt[4]{SINR_{6\,\text{Mbps}}} \times d$. In Table 1, $SINR_{6\,\text{Mbps}}$ is 6.02 decibel (dB), which indicates that the ratio of P_r to $\Sigma_i P_i$ is 4 and thus $d_{i,ctr}$ becomes $1.414 \times d$. In IEEE 802.11a, the thresholds for energy detection and carrier detection are -62 and -82 dBm respectively [6]. In addition, the minimum receiver sensitivity level for a frame with 6 Mbps, which is required for successful RTS/CTS receptions, is -82 dBm (see Table 1). Therefore, we can say that carrier sensing range is completely covered by NAV set range [13]. This is a unique feature of 802.11a PHY since it has been known that carrier sensing range is much larger than NAV set range in other 802.11 PHYs such as 802.11b. We found that the probability of transmitter side frame loss (e.g., CTS and ACK) in IEEE 802.11a WLANs is much higher than that in 802.11b or 802.11g WLANs. For example, Fig. 2 shows the radio ranges of IEEE 802.11a wireless networks. The radius of carrier sensing range is not marked in the figure since it is the same as d_{nav}. In the figure, the transmissions of N1 and N2, that are located inside of the interference range and outside of the carrier sensing range of S and D respectively, may interfere with frame receptions at S and D. Therefore, S may fail to receive CTS and ACK by the interference of N1, and D may fail to receive RTS and DATA by the interference of N2.

Now we discuss the effect of each frame loss on the system performance.

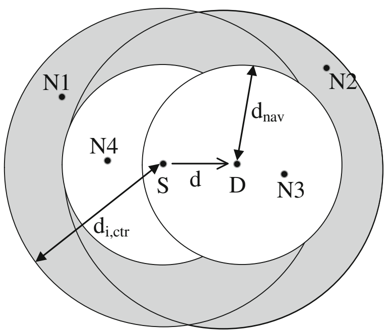

Fig. 2 Radio ranges in IEEE 802.11a wireless networks

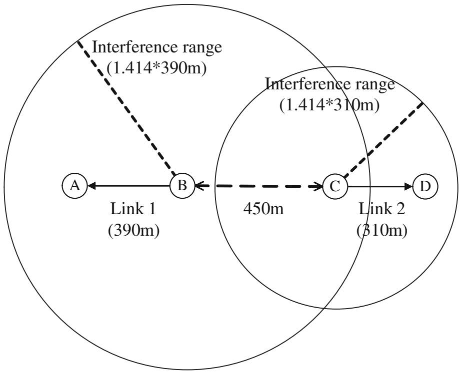

Fig. 3 A sample topology with two links

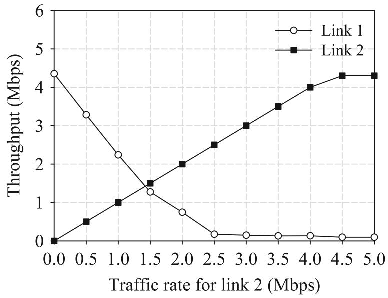

Fig. 4 The network throughput of a simple topology

- DATA losses cause DATA retransmissions, which leads to low network throughput. As discussed above, several solutions [18,9,20,11,15,17,3,8] have been proposed to reduce DATA losses.
- ACK losses also cause DATA retransmissions. However, existing solutions do not focus on the effect of control frame losses.
- RTS or CTS losses let neighbor nodes that overheard the RTS or CTS unnecessarily waste the medium during the time duration set by NAV. The wasted area by CTS losses is larger than that by RTS losses.

The transmitter side frame loss decreases network performance, just as the receiver side frame loss. In order to see how much transmitter side frame loss affects network performance, we performed ns-2 simulations. We generated a simple topology with two links as shown in Fig. 3, where B and C have frames to be transmitted to A and D, respectively. The data rate for the frames is set to 6 Mbps whose transmission range is 400 m, and thus the carrier sensing range, transmission range, and NAV set range are the same. The distances between A and B, B and C, and C and D are set to 390, 450, and 310 m, respectively, so that C is located inside of B's interference range (i.e., 1.414×390 m) while B is located outside of C's interference range (i.e., 1.414×310 m). Thus, B's frame reception may be interfered with C's transmission, while C's frame reception cannot be interfered with B's transmission. In order to observe the impact of C's traffic rate on B's control frame loss, we set the traffic rate of B remains constant (5 Mbps), while the traffic rate of C varies from 0 to 5 Mbps. Figure 4 shows the throughput of both link 1 and link 2. We can see that when the traffic rate of C increases, link 1's throughput decreases severely. The main reason for the result is that the loss ratio of CTS and ACK in B increases as the traffic rate of C increases. In contrast, link 2 does not suffer from interference by B. From the simulations, we can find that CTS and

ACK losses by interferences can aggravate network throughput. We can also find that if a link distance is short (e.g., 310 m in Fig. 3), transmitter side losses by interference do not occur. Although some existing approaches [18,9,17,3,8] can reduce CTS and ACK losses at receiver, these approaches have their own limitations such as lower network connectivity due to reduced effective transmission range [18] and the requirement of additional hardware [9,17,3,8].

4 Robust and Cooperative MAC Protocol

In this section, we propose an enhanced MAC protocol, called *Robust and Cooperative MAC* (RCMAC), which exploits the relay mechanism to reduce CTS and ACK losses at a transmitter. In RCMAC, CTS and ACK frames are relayed via relay nodes in order to increase the received signal strength at a transmitter. First, we describe the relay node notification procedure that allows both the transmitter and receiver to know candidate relay nodes. Then, we describe the medium access operation in RCMAC.

4.1 Relay Node Notification

If a node can be a relay node for a link between a transmitter and receiver, it notifies the fact to them by using a control message. When a node finds that frames on a link can be transmitted faster by two-hop transmissions via itself than by a direct transmission, it can act as a relay node. The supportable transmission rate between two nodes can be determined by the channel condition based on Table 1. A relay node that overhears RTS and CTS measures the received signal strength of RTS and CTS. However, since the relay node does not know the interference level of the receiver from the overheard CTS, it is difficult to measure the transmission rate from itself to the receiver. To handle this, we modified both RTS and CTS so that they include interference information. For the interference information, we use the *Average Interference Level* (AIL) metric to handle dynamically changeable interferences. Since the interference level at a node can change dynamically even during a DATA transmission, the interference level that is measured from RTS at the receiver may be incorrect in the DATA transmission phase. Thus, we approximately measure the average interference level. A node periodically measures the current interference level (we used 10 ms in our simulation study). Then, it computes AIL_{new} by adopting the following weighted averaging technique:

$$AIL_{new} = (1-\alpha) \times AIL_{old} + \alpha \times IL \tag{3}$$

where $\alpha \in [0, 1]$, AIL_{old} is the current AIL, and IL is the currently measured interference level.

Based on *AIL* and overheard RTS and CTS, the relay node obtains the following transmission rate information. First, the relay node (R) knows the transmission rate from the transmitter (S) to receiver (D) (i.e., R_{SD}) based on CTS which includes R_{SD}. Second, R calculates the transmission rate from itself to D (i.e., R_{RD}) based on *AIL* and the measured received signal strength of CTS. Last, R calculates the transmission rate from S to itself (i.e., R_{SR}) based on both the overheard RTS and *AIL*. Thus, R can determine whether the frame transmission via itself (i.e., two-hop link S → R → D) is faster than that via the direct link (i.e., S → D) or not. If the relay transmission is faster, then R acts as a relay node. In this case, R adds the MAC addresses of S and D, R_{SR}, and R_{RD} to its relay list as an entry.

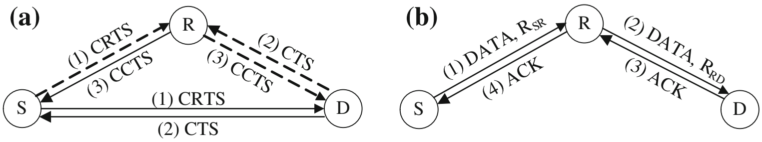

Fig. 5 Data and control frame transmissions: (**a**) CRTS, CTS, and CCTS transmissions (**b**) DATA and ACK transmissions

R periodically advertises its relay list to its one-hop neighbors. If a node that receives the advertised message finds its MAC address in the received relay list, it stores the information, such as the MAC addresses of D and R, R_{SR}, and R_{RD}, in the relay table. The table can be updated with recent information whenever receiving advertisement messages or control frames (e.g., RTS, CTS, etc). Each entry in the table is maintained by a timer to remove stale information. If the node cannot receive it again until the expiration of the timer, the node deletes the expired information from the table.

4.2 Medium Access Operation

S has DATA with L bytes size to transmit to D, it has to make a decision to choose a transmission scheme between RCMAC and Receiver Based Auto Rate (RBAR, a well-known closed-loop rate adaptation protocol based on DCF) [4]. First, S looks up its relay table to find relay nodes for D. If there is no entry for D, then RBAR is applied. If there exist one or more entries for D, S calculates T_{RCMAC} for each entry which is the required time for transmitting DATA via R in RCMAC, which is expressed as follows;

$$T_{RCMAC} = T_{CRTS} + T_{CTS} + T_{CCTS} + 2T_{ACK} + T_{DATA}(L, R_{SR}) + T_{DATA}(L, R_{RD}) + 6SIFS$$

where T_{CRTS}, T_{CTS}, T_{CCTS}, and T_{ACK}, are the transmission times for Cooperative RTS (CRTS), CTS, Cooperative CTS (CCTS), and ACK respectively, $T_{DATA}(L, R_{SR})$ is the transmission time of DATA with the transmission rate of R_{SR}, and $T_{DATA}(L, R_{RD})$ is the transmission time of DATA with the transmission rate of R_{RD}. Then, S selects an entry for R with the minimum T_{RCMAC}. Now, S determines whether the time spent for DATA transmission via RCMAC is smaller than it or not via DCF by checking the following condition:

$$T_{RCMAC} \leq T_{DCF} \tag{4}$$

where $T_{DCF} = T_{RTS} + T_{CTS} + T_{ACK} + T_{DATA}(L, R_{SD}) + 3SIFS$. If Eq. 4 satisfies, then S initiates a new handshake procedure of RCMAC. If not, S initiates the four-way handshake (i.e., RTS-CTS-DATA-ACK) procedure of RBAR.

Figure 5 illustrates the handshake procedure in RCMAC, where a dashed arrow indicates that the target node can overhear the corresponding frame, and a solid arrow indicates that the corresponding frame is destined to the target node. S sends CRTS to D, where CRTS includes R's MAC address and S's AIL. When D receives CRTS, it replies with CTS, which piggybacks both R_{SD} and its' AIL to S. Upon overhearing both CRTS and CTS, R knows whether it is selected as the relay node or not and it obtains the following information from them: AIL of both S and D, the measured received signal strengths for S and D, and R_{SD}. Using the information, R determines R_{SR} and R_{RD}. Then, R makes a decision whether it should perform DATA transmission as a relay node or not by checking Eq. 4. If R decides to participate as a relay node, then it makes CCTS and determines whether it should relay ACK or not. Under good channel conditions in which a high ACK reception probability is

Table 2 The NAV duration in proposed protocol

Frame type	The duration
RTS	$T_{CTS} + SIFS + \sigma$
CTS	if(received frame is RTS)
	$T_{DATA}(L{,}R_{SD}) + T_{ACK} + 2SIFS + 2\sigma$
	if(received frame is CRTS)
	$T_{CCTS} + T_{DATA}(L{,}R_{SR}) +$
	$T_{DATA}(L{,}R_{RD}) + 2T_{ACK} + 5SIFS + 5\sigma$
CRTS	$T_{CTS} + T_{CCTS} + 2SIFS + 2\sigma$
CCTS	$T_{DATA}(L{,}R_{SR}) + SIFS + \sigma$
DATA	if(ACK relaying)
(S → R)	$T_{DATA}(L{,}R_{RD}) + 2T_{ACK} + 3SIFS + 3\sigma$
	else
	$T_{DATA}(L{,}R_{RD}) + T_{ACK} + 2SIFS + 2\sigma$
DATA	if(ACK relaying)
(R→D)	$2T_{ACK} + 2SIFS + 2\sigma$
	else
	$T_{ACK} + SIFS + \sigma$
DATA	$T_{ACK} + SIFS + \sigma$
(S→D)	
ACK	0

guaranteed, ACK relaying may be useless and will become time waste ($T_{ACK} + SIFS$). Thus, ACK is relayed only if the following condition satisfies:

$$SINR_{RX} = \frac{P_r}{P_i} \leq SINR_{6\,\mathrm{Mbps}} \tag{5}$$

where P_r is the received signal strength of CRTS at R, P_i is the AIL of S. Equation 5 means that S's channel condition is not good enough to successfully receive frames from D. Now, R sends CCTS to S, which includes R_{SR}, R_{RD}, and the information about whether ACK relaying is used or not. D that overheard CCTS knows whether it has to send ACK to R (ACK relaying) or S, when it receives DATA. We use three values among the reserved subtype values (0000–1001) of the control type field in [5] to distinguish CRTS, CCTS with ACK relaying, and CCTS without ACK relaying.

When S receives CTS from D, it should wait for CCTS from R. If S does not receive CCTS until the expected reception time (i.e., $SIFS + T_{CCTS}$), then the subsequent DATA and ACK are exchanged directly between S and D. CCTS is used for notifying S that DATA relaying is used. It also notifies S whether ACK relaying is used or not by setting a field in it. CCTS can be regarded as CTS to S since R can send CCTS only when it overhears CTS from D. Thus, although S did not receive CTS, if it receives CCTS successfully, then DATA can be transmitted via R. In this way, CTS losses can be reduced.

After that, S transmits DATA to R with R_{SR} as shown in Fig. 5b. On receiving DATA, R sends it to D with R_{RD} after a SIFS. When D correctly receives DATA through R, it sends ACK to R (i.e., ACK relaying) or to D (i.e., direct ACK transmission) based on the subtype of CCTS. Through ACK relaying, the time wasted for DATA retransmissions by ACK losses can decrease when the probability of interference induced ACK collisions is high. Table 2 lists the NAV duration for each frame used in RCMAC.

Table 3 Simulation parameters for IEEE 802.11a specification

Parameters	Values
PLCP overhead	328 bits (PLCP preamble (288 bits), PLCP header (40 bits))
Slot	9 μs
SIFS	16 μs
DIFS	34 μs
CWmin	15
CWmax	1023

5 Performance Evaluation

5.1 Simulation Environments

We evaluated the performance of RCMAC using ns-2 [16] and compared it with RBAR and rDCF. We performed simulations assuming all nodes are moving based on the random waypoint mobility model. Each node uses a fixed transmission power of 15dBm to transmit frames, and the carrier sensing threshold at each node is set to −82 dBm. Furthermore, the thermal noise level is set to −101 dBm. When the transmission power is 15 dBm, the transmission range for data rate of 6 Mbps is about 400 m. For PHY and MAC layer parameters, we followed the specification of IEEE 802.11a [6] shown in Table 3. In addition, we used the two-ray path loss model [14] as the radio propagation model. We considered UDP traffic, whose packet size is 1,024 bytes. The performance metrics include aggregate throughput in single hop flow scenario (or packet delivery ratio in multi-hop flow scenario), end-to-end delay, and throughput fairness index ($F_{throughput}$), collision ratio. The aggregate throughput is the total sum of received DATAs at receivers divided by the simulation time. The end-to end delay, which is averaged over all flows in each scenario, includes both the transmission delay and queuing delay. The Jain's fairness index [7] is used to measure the throughput fairness among different flows, which is represented as follows:

$$F_{throughput} = \frac{(\Sigma_i throughput_i)^2}{N \times \Sigma_i throughput_i^2} \qquad (6)$$

where N is the number of nodes and $throughput_i$ is the throughput of node i.

5.2 Performance of One-Hop UDP Flow Scenarios

We observed the impact of one-hop UDP traffic on network performance by varying the offered traffic load per flow from 300 Kbps to 1.5 Mbps. The number of flows in the network is 50 where the source and destination of a flow are randomly selected. Nodes move around the network randomly with the maximum node speed of 5 m/s, while sources and destinations are fixed to keep the distances among them. We generate 20 random topologies (scenarios) and 20 simulation results per each flow rate are averaged. The simulation time is 100 s.

Figure 6a–c show the aggregate throughput, end-to-end delay, and throughput fairness as a function of flow rate, respectively. When the offered flow rate increases, the aggregate throughput and end-to-end delay increases, while the throughput fairness decreases. As shown in the figures, RCMAC shows enhanced performance over both rDCF and RBAR. For example, Fig. 6a shows that the aggregate throughput by RCMAC is 6.1 and 2.3% higher

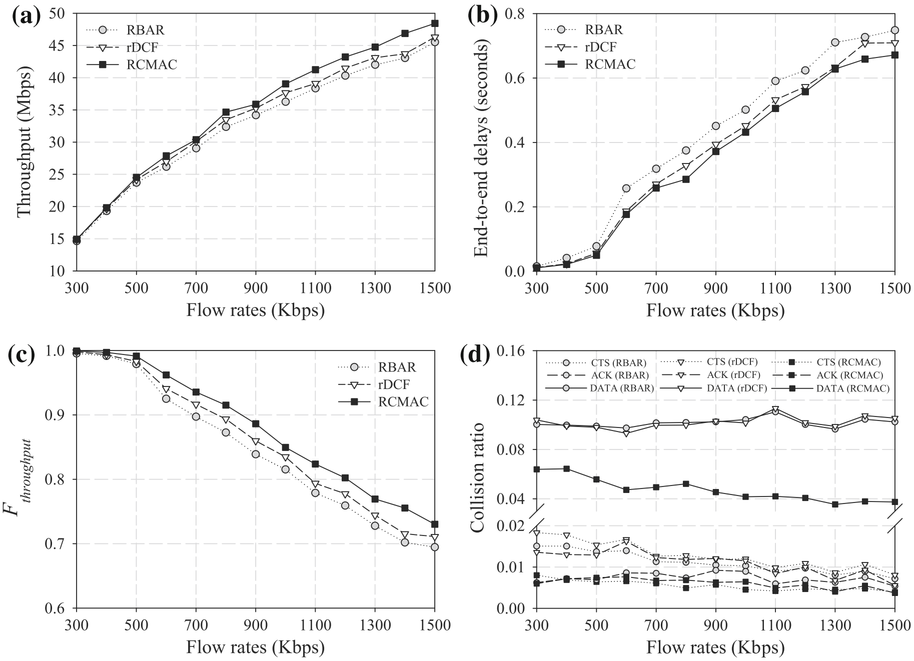

Fig. 6 Performance of one-hop flows according to flow rates: (**a**) aggregate throughput, (**b**) average end-to-end delays, (**c**) $F_{throughput}$, (**d**) collision ratio

than RBAR and rDCF, respectively, when the flow rate is 700 Kbps. In addition, from Fig. 6b, we can see that the end-to-end delay by RCMAC is 28.6 and 16.1% lower than RBAR and rDCF, respectively, when the flow rate is 700 Kbps. RCMAC also shows 4.9 and 2.6% better throughput fairness performance than RBAR and rDCF, respectively, when the flow rate is 700 Kbps as shown in Fig. 6c.

The reason for the performance improvement of RCMAC is as follows. As the flow rate increases, the number of contending links in the network increases and the contending links experience more interference. Thus, the probability of control frame losses of long distance links increases. Figure 6d shows the collision ratio of CTS, ACK, and DATA frames. Since the impact of RTS losses is not so great as mentioned in Sect. 3, we omit the collision ratio of RTS in the figure. The collision ratio means the number of collisions divided by the number of transmissions. As shown in Fig. 6d, RCMAC's collision ratios for CTS, ACK, and DATA are less than those of RBAR and rDCF. Thanks to the reduction of frame losses, RCMAC shows improved performance. The reason why RCMAC alleviates frame losses is that the control frame relaying mechanism in RCMAC leads to robust control frame (CTS and ACK) receptions. In addition to this, RCMAC can obtain extra throughput gain by reducing DATA losses since it can select a robust transmission rate based on AIL.

We executed additional simulations under specific environments where ACK and CTS losses may be generated more frequently than the previous simulation environment. For this, we generated randomly selected 50 one-hop flows under the condition that the distance of each transmitter-receiver pair is from 300 to 400 m. The other simulation parameters and environments are the same as those used in the previous simulations. Figure 7a–c show the aggregate throughput, end-to-end delay, and throughput fairness, respectively, as a function

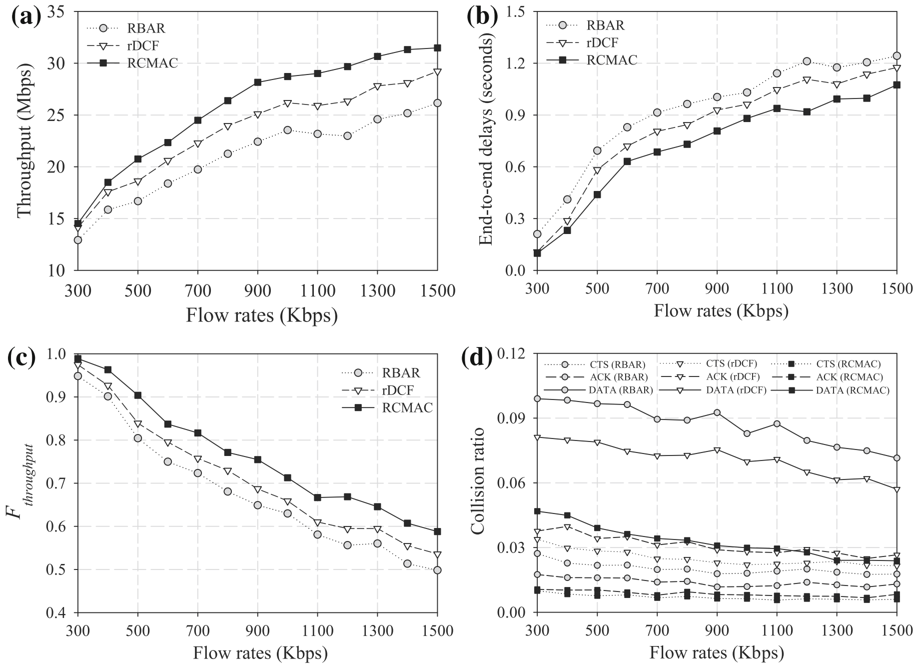

Fig. 7 Performance of one-hop flows according to flow rates (flow distance is 300–400 m): (**a**) aggregate throughput, (**b**) average end-to-end delays, (**c**) $F_{throughput}$, (**d**) collision ratio

of flow rate. Similar to the previous simulations, RCMAC outperforms RBAR and rDCF in terms of all metrics. Also, the degree of performance improvement of RCMAC over the two protocols is much higher than that of the previous scenario. This is because the loss probability of both CTS and ACK increases in the scenario (Fig. 7d) compared with that in the previous scenario (Fig. 6d) although the degree of reduction of DATA collision ratio is similar to that of the previous scenario. Thus, we can know that the main reason of performance improvement comes from the reduction of CTS and ACK losses rather than the reduction of DATA losses. As an example, we look into the performance results when the flow rate is 1,100 Kbps in Fig. 7. In Fig. 7a, RCMAC's aggregate throughput is 22.9 and 9.9% higher than that of RBAR and rDCF, respectively, when the flow rate is 1,100 Kbps. Also, Fig. 7b shows that the end-to-end delay of RCMAC is 17.9 and 10.5% lower than that of RBAR and rDCF, respectively, when the traffic rate is 1100 Kbps. Last, from Fig. 7c, we can see that the throughput fairness of RCMAC is 16.1 and 10.5% better than that of RBAR and rDCF, respectively, when the traffic rate is 1,100 Kbps.

To examine the impact of the packet size on the performance, we varied the size of packets from 128 to 1024 bytes, where the number of flows is 50, the distance of each transmitter-receiver pair is between 300 and 400 m, the number of nodes is 200, and the flow rate is 1,000 Kbps. All nodes are randomly distributed in a 2,500 by 2,500 m area, and the other simulation parameters are the same as those used in the previous simulations. Tables 4, 5, 6 show the aggregate throughput, end-to-end delay, and throughput fairness of RCMAC, rDCF, and RBAR for several packet sizes. When the packet size is small (128 or 256 bytes), RBAR, rDCF and RCMAC show very comparable performance for the three performance metrics. This is because when the packet size is small, relay MAC protocols such as rDCF

Table 4 Aggregate throughput Mbps according to the packet size

	128 bytes	256 bytes	512 bytes	1024 bytes
RBAR	11.1	16.4	20.4	23.5
rDCF	10.9	16.1	22.0	26.2
RCMAC	10.8	16.1	23.2	28.7

Table 5 Average delay (seconds) according to the packet size

	128 bytes	256 bytes	512 bytes	1024 bytes
RBAR	0.87	0.87	0.95	1.03
rDCF	0.91	0.91	0.91	0.96
RCMAC	0.91	0.92	0.77	0.88

Table 6 Throughput fairness according to the packet size

	128 bytes	256 bytes	512 bytes	1024 bytes
RBAR	0.42	0.50	0.59	0.63
rDCF	0.41	0.51	0.61	0.66
RCMAC	0.41	0.50	0.66	0.72

and RCMAC may not get relay gains. However, when the packet size becomes large (512 or 1,024 bytes), RCMAC outperforms the other protocols. For example, the aggregate throughput of RCMAC is 13.7% and 5% higher than RBAR and rDCF, respectively, when the packet size is 512 bytes. Also, we can see that RCMAC improves the end-to-end delay (or throughput fairness) performance about 14.5 and 8.5% (or 21.9 and 10.1%) over RBAR and rDCF, respectively, when the packet size is 1,024 bytes.

5.3 Performance of Multi-Hop UDP Flow Scenarios

Next, we performed simulations using multi-hop UDP flows to show the advantages of the RCMAC protocol in multi-hop mobile ad-hoc network environments. 100 nodes are randomly distributed in a 1,500 m by 1,500 m area and nodes move around with the speed of at most 5 m/s. The AODV routing protocol [12] is used as the routing protocol. We generate 20 random topologies (scenarios), 20 simulation results per each flow rate are averaged, and the simulation time is 200 seconds. We observed the performance of RCMAC and the two comparing protocols by changing the flow rate and the number of flows.

Figure 8a–c show the network performance when the number of multi-hop UDP flows is 20, while the flow rate changes from 60 to 160 Kbps. As shown in the figure, compared

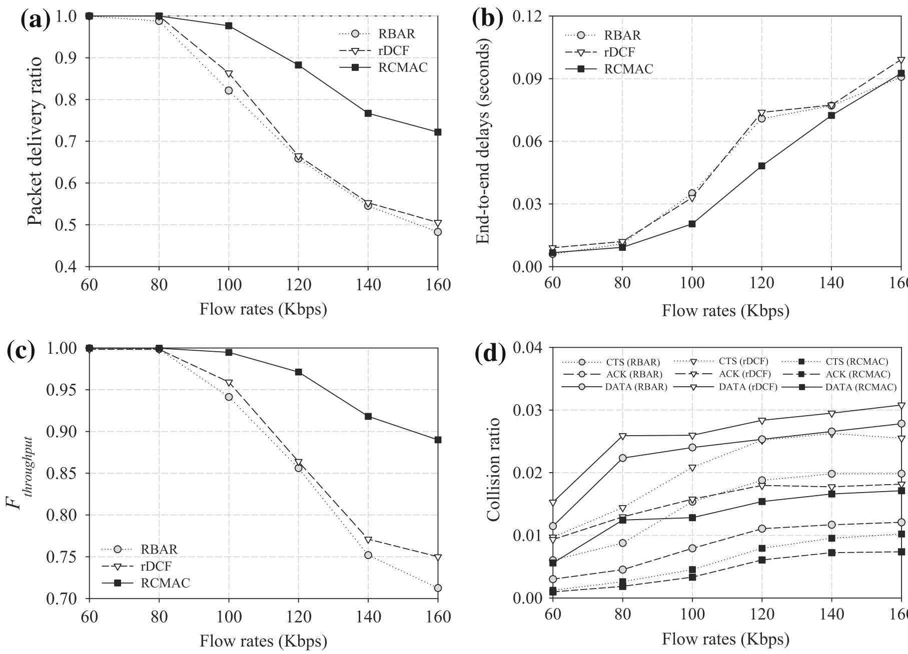

Fig. 8 Performance for multi-hop UDP flows according to flow rates: (**a**) packet delivery ratio, (**b**) average end-to-end delays, (**c**) $F_{throughput}$, (**d**) collision ratio

to both rDCF and RBAR, RCMAC achieves improved network performance in terms of packet delivery ratio, delay, and throughput fairness for flow. For example, Fig. 8a shows that the packet delivery ratio by RCMAC is 34.1 and 32.8% higher than RBAR and rDCF, respectively, when the flow rate is 120 Kbps. In addition, from Fig. 8b, we can also witness about 32.1 and 34.8% improvement in end-to-end delay by RCMAC over RBAR and rDCF, respectively, when the flow rate is 120 Kbps. RCMAC also outperforms RBAR and rDCF by 13.4 and 12.4%, respectively, in terms of throughput fairness per flow. From the results, we can see that RCMAC shows much better performance in multi-hop network environment than single-hop network environment. The main reason for these results is that RCMAC can reduce the occurrences of false route failures [2] since it can alleviate CTS, DATA, and ACK loss ratio as shown in Fig. 8d. Route failure alarms are generated by the MAC layer to notify the routing layer of the route disconnection, which triggers a new route discovery procedure. Until a new route is found, the packets will experience a large delay. The route discovery procedure also causes Route Request (RREQ) flooding which wastes network bandwidth and becomes another interference source. The degree of false alarms is more serious as the increase of flow rates. Thus, when increasing flow rates, the packet delivery ratio, end-to-end delay, and fairness for all protocols deteriorate. However, the performance of RCMAC is better than other two protocols regardless of the flow rate.

To show the impact of the number of flows on network performance, we varied the number of flows from 30 to 60 where the flow rate is 50Kbps. Figure 9a–c illustrate the packet delivery ratio, end-to-end delay, and throughput fairness for flow of RCMAC, rDCF, and RBAR. With the same reason mentioned in multi-hop UDP flow scenarios when flow rates varies,

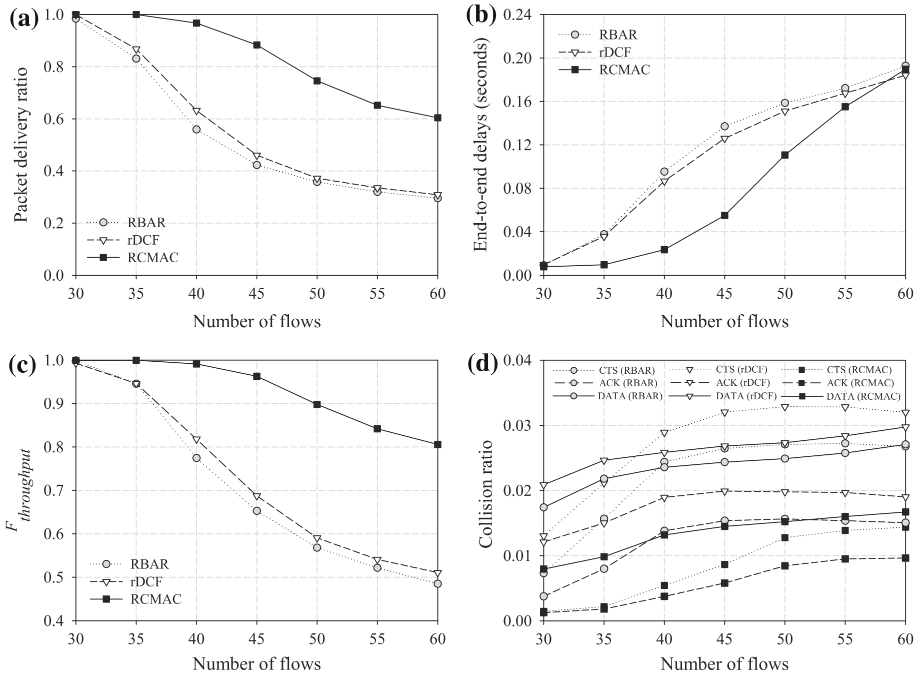

Fig. 9 Performance for multi-hop UDP flows according to the number of flows: (**a**) packet delivery ratio, (**b**) average end-to-end delays, (**c**) $F_{throughput}$, (**d**) collision ratio

RCMAC achieves improved packet delivery ratio and end-to-end delay in most cases. When the number of flows is small (30 or less), the three protocols show similar results for all performance metrics. However, as increasing the number of flows, the performance improvement of RCMAC over the other two protocols also increases. For example, RCMAC shows 20 and 15% improved packet delivery ratio performance over RBAR and rDCF, respectively, when the number of flows is 35. However, we can see that the packet delivery ratio by RCMAC shows 108 and 100% improvements over RBAR and rDCF, respectively, when the number of flows is 50.

6 Conclusion

In this paper, we first presented the impact of interference at the transmitter due to the characteristic feature on the carrier sensing range of IEEE 802.11a wireless networks. Interferences can prevent transmitters from receiving control frames. We proposed an enhanced MAC protocol, called Robust and Cooperative Medium Access Control (RCMAC) to reduce control frame losses at transmitters. RCMAC utilizes the CTS and ACK relaying via a possible relay node, by which transmitters can achieve high reception probability of control frames. We performed extensive ns-2 simulation to evaluate the performance of the proposed RCMAC protocol. The simulation results show that the performance of RCMAC is better than the legacy 802.11 DCF and an existing relay-based MAC protocol.

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