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RESEARCH ARTICLE

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An adaptive cooperative MAC protocol compatible with legacy 802.11 DCF

Abstract A novel adaptive cooperative medium access control (MAC) protocol, which is completely backward compatible with the legacy IEEE 802.11 distributed coordination function (DCF), is proposed in this paper. To adapt to dynamic channel variation and network topology, the sender adaptively selects transmission scheme based on the instantaneous channel measurements. Analytical and simulation results show that the proposed protocol outperforms the existing one in terms of throughput, delay, energy and mobility.

Keywords cooperative communication, medium access control (MAC), distributed coordination function (DCF)

1 Introduction

Recently, more and more researchers focus on cooperative communications in wireless networks. The scheme of cooperation takes full advantage of the broadcast nature of the wireless channel and creates spatial diversity gains by allowing different nodes in a wireless network to share their resources, thereby achieving tremendous improvement in system robustness, capacity, and delay, a significant reduction in interference, and extension of coverage range.

Research and application of cooperation at MAC layer receive little attention until recently, though it has motivated extensive research activities in information theory and communications communities. Cooperative medium access control (CoopMAC) [1] and relay-enabled distributed coordination function (rDCF) [2] are the cooperative medium access control (MAC) protocols based on the distributed coordination function (DCF) of IEEE 802.11. Both protocols take advantage of the multi-rate capability of IEEE 802.11 physical layer standard, and the basic ideas in them are similar. A slow node, instead of sending its packets at a low rate to a destination directly, uses an intermediate station between the sender and the receiver and is able to transmit at a high rate in a two-hop manner. However, there are some problems in the aforementioned literatures. Firstly, they assume that each station pre-assigns a relay node before transmitting its packets by maintaining a relay table. However, this proactive relay selection may not adapt to dynamic channel condition and network topology in wireless networks, and furthermore, it is complicated and energy-consuming to maintain this kind of relay list. Secondly, additional control overheads are introduced, and the legacy frame control format is changed to facilitate the cooperation, which causes the protocol unable to be compatible with the legacy 802.11 DCF. Lastly, a complicated analytical model based on 2-dimensional Markov chains is adopted to evaluate performance. Other cooperative MAC protocols based on CoopMAC are given in literatures. In Ref. [3], busy tone based cooperative (BTAC) protocol based on CoopMAC is proposed in which a busy tone signal instead of helper-to-send (HTS) that is in CoopMAC is used in order to reduce overheads. However, the shortcoming of BTAC is that the neighboring nodes cannot accurately get network allocation vector (NAV) which causes increase of packet collisions. In Ref. [4], CoopMAC protocol is extended into the ad hoc network environment, and performance analysis is given under a large-scale scenario. Reference [5] provides new cross-layer research directions and describes how physical-layer cooperation can be integrated with the MAC sublayer for dramatic improvements in throughput and interference. A novel opportunistic cooperative MAC protocol (OC-MAC) [6] is proposed based on cross-layer information utilization, and opportunistic cooperative strategy is described to use relay only when it can improve the performance of the network system. A cooperative relay-

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based auto-rate MAC protocol (CRBAR) proposed in Ref. [7] suggests that the relay candidates adaptively select themselves as the relay nodes and determine the relay scheme and transmission rates based on the instantaneous channel measurements. The aforementioned cooperative MAC protocols are all based on the DCF of IEEE 802.11. Reference [8] proposes relay-enabled point coordination function (rPCF) protocol, which enables multi-hop in the point coordination function (PCF) mode. However, PCF mode is seldom used and has limited applications.

To fully leverage the benefits of cooperation at the MAC layer, in this paper, we propose an adaptive cooperative MAC (ACoopMAC) protocol based on channel feedback. The novel protocol adopts new frame control formats and is completely compatible with the legacy 802.11 DCF. To adapt to dynamic channel variation and network topology, the sender adaptively selects a transmission scheme based on the instantaneous channel measurements.

This paper is organized as follows. The system model is described in Sect. 2. In Sect. 3, ACoopMAC is introduced in detail. Analytical and simulation results are given in Sect. 4. Finally, conclusions are made in Sect. 5.

2 System model

The system model adopted in this paper is shown in Fig. 1. Improved ready-to-send/improved clear-to-send (IRTS/ICTS) are control frames adopted in the proposed protocol that are modified frameworks of legacy request to send/clear to send (RTS/CTS). And improved helper-to-send (IHTS) is a new message introduced to facilitate the cooperation, which will be sent by the helper if it agrees to assist source to forward packets. It is also assumed, for simplicity, that the transmission power of each station is fixed, and the wireless channel between any two stations is assumed symmetric since all stations use the same frequency band for transmission and reception.

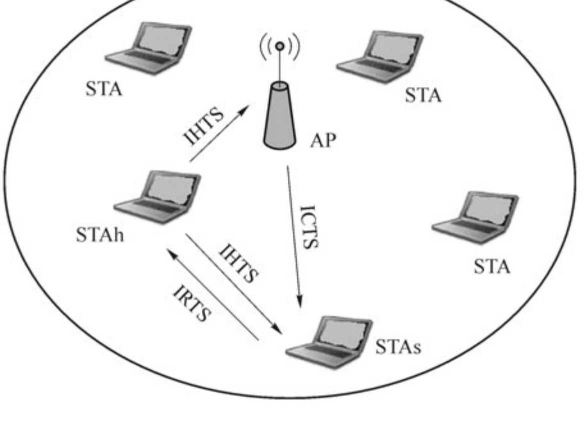

Fig. 1 System model

Each station maintains a table of potential helpers around itself, similar to CoopMAC protocol but simpler than it. Each row of this table has three fields. One is the address of potential relay. The second field is R_{sh}, which is the data rate from source to helper. The last is R_{hd}, which is the data rate between helper and access point (AP). Once a source station has data of length L octets to transmit to AP, it will first check the relay table to decide whether to transmit through a particular helper. Ignoring the overhead, the transmission time for such a two-hop transmission is $8L/R_{\mathrm{sh}} + 8L/R_{\mathrm{hd}}$, and the direct transmission time between transmitter and AP is $8L/R_{\mathrm{sd}}$, where R_{sd} is the data rate from source station to AP. The helper that satisfies the following equation through which the minimum transmission time can be achieved will be chosen as the candidate relay:

$$\frac{8L}{R_{\mathrm{sh}}} + \frac{8L}{R_{\mathrm{hd}}} < \frac{8L}{R_{\mathrm{sd}}}. \tag{1}$$

Since information recorded in the helper table may be out of date, this relay selection scheme may not adapt to dynamic channel condition and network topology in wireless networks. In the proposed protocol, we will determine again based on channel feedback whether the sender directly transmits to AP or forwards through the helper. The helper and AP can estimate the channel condition between themselves and the sender by measuring the received IRTS message strength. By checking the threshold value, which is pre-calculated and guarantees a certain bit error rate for each modulation scheme, we can find the corresponding data rate R_{sh} and R_{hd}. Both data rates can be piggybacked in IRTS or ICTS (details in Sect. 3) and transmitted to the sender, which decreases the control packet overheads and energy-consuming. And then the sender updates the helper table according to the acquired data rate; furthermore, it determines whether Eq. (1) is still satisfied or not. If the condition is not satisfied, the sender will transmit directly to AP; otherwise, it will send packet through a helper. Thus, the proposed protocol is robust against the channel conditions and network topology.

3 Proposed protocol

In this section, we will give details of the proposed ACoopMAC that is completely backward compatible with the legacy 802.11 DCF. The key function of ACoopMAC is adaptive selection of transmission scheme and piggyback transporting technique of data rate based on the instantaneous channel measurements.

The main differences between ACoopMAC and CoopMAC are as follows:

1) In the IRTS frame, the legacy resource address (RA) segment is replaced by the XORing identification (ID) of the transmitter and AP, and the helper ID instead of the legacy TA segment (see Fig. 2). Thus, the IRTS length is

equal to the legacy RTS frame in IEEE 802.11 and less than the CoopMAC protocol. Compared with the CoopMAC RTS frame, in the IRTS frame, there are one ID field that is saved and two rate segments, R_{sh} and R_{hd}, which are transmitted to the sender by channel feedback, that are subtracted from the frame. Being the type field, value 11 in the frame control of the MAC header is reserved, so it can be used to distinguish the IRTS packet and the legacy RTS packet.

2) Since the last octets of the two bytes of the frame control field in the control frame are not specific usage, the data rate can be piggybacked in it (see Figs. 3 and 4), which may decrease the control packet overheads and meanwhile maintain the integrality of the IHTS frame. Multi-rate is supported in IEEE 802.11; for instance, there are four kinds of data rate: 1 Mbit/s, 2 Mbit/s, 5.5 Mbit/s and 11 Mbit/s in IEEE 802.11b. Therefore, one byte can completely indicate the data rate via a piggyback mechanism.

3) In particular, a cooperation flag (CF) bit in ICTS is introduced to indicate whether adopting cooperation or not. The CF value 1 means cooperation and value 0 for direct transmission.

4) The source station will determine the transmission mode according to whether the IHTS frame is received or not, together with the format of the ICTS frame, which makes ACoopMAC more robust.

The detailed handshaking scheme and transmission process are summarized using the following algorithm.

1) Send IRTS = {STAs broadcasts IRTS frame};

2) Send IHTS = {STAh sends IHTS to AP and STAs};

3) Send ICTS = {AP sends ICTS to STAs and STAh};

4) Determine transmission mode = {STAs chooses transmission mode according to the data rate obtained from IHTS and ICTS };

5) If cooperative transmission then

a) Send DATA1 = {STAs broadcasts its data to STAh and AP at rate R_{sh}},

b) Send DATA2 = {STAh forwards the DATA1 to AP at rate R_{hd}},

c) Send ACK = {AP sends acknowledgement (ACK) packet to STAs if correct DATA after decoding DATA1 and DATA2};

6) Else direct transmission then

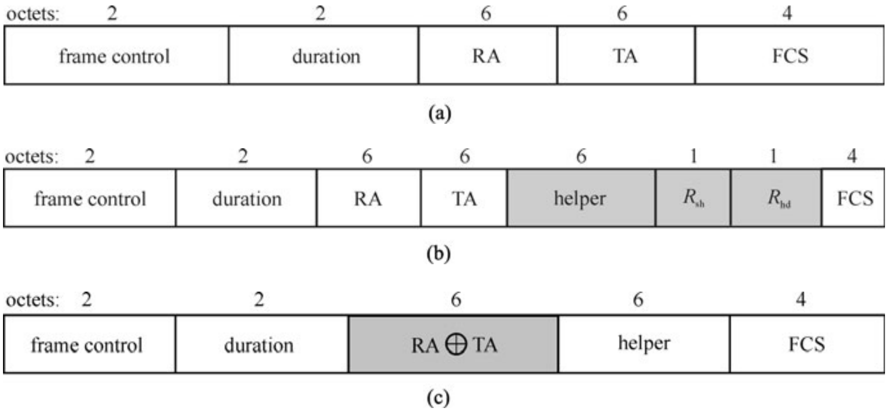

Fig. 2 Frame format. (a) 802.11 RTS; (b) CoopMAC RTS; (c) IRTS

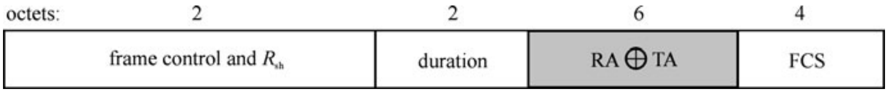

Fig. 3 Frame format for IHTS

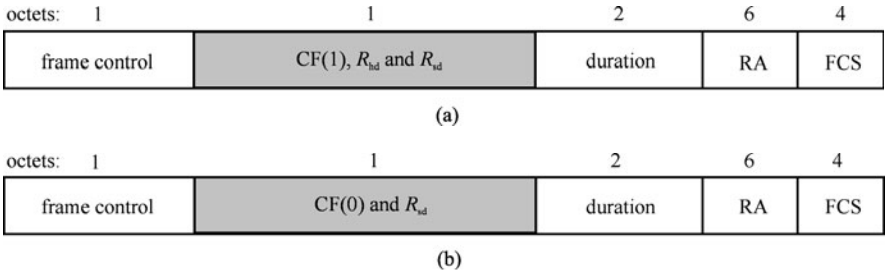

Fig. 4 Frame format for ICTS. (a) Cooperation ICTS; (b) direct transmission ICTS

a) Send DATA ={STAs sends DATA to AP at rate R_{sd}},

b) Send ACK ={AP sends ACK packet to STAs if correct DATA};

7) Return to step 1).

4 Analytical and simulation results

In this section, we will evaluate performance of our proposed adaptive cooperative MAC protocol in a saturated network. All nodes are uniformly distributed in the coverage area and are assumed to be stationary.

The normalized system throughput S is defined as the fraction of time; the channel is used to successfully transmit payload bits.

$$S = \frac{\mathrm{E[payload\ information\ tranmitted\ in\ a\ slot\ time]}}{\mathrm{E[length\ of\ a\ slot\ time]}} = \frac{P_{\mathrm{s}}P_{\mathrm{tr}}\mathrm{E}[P]}{(1-P_{\mathrm{tr}})\sigma + P_{\mathrm{tr}}P_{\mathrm{s}}T_{\mathrm{s}} + P_{\mathrm{tr}}(1-P_{\mathrm{s}})T_{\mathrm{c}}}, \tag{2}$$

where σ is the duration of a slot time; E[P] is the average packet length and is a fixed value (equal to L bytes) in this paper; T_{s} and T_{c} are the average successful transmission slot time and the average collision slot time, respectively; P_{tr} is the probability that there is at least one transmission in the considered slot time; P_{s} is the probability that a transmission occurring on the channel is successful.

Let τ denote the probability that the station transmits in a randomly chosen slot, and p is the probability that a packet transmitted shall collide. Assume that there are n stations in the network, and then we have

$$P_{\mathrm{tr}} = 1-(1-\tau)^n, \tag{3}$$

$$P_{\mathrm{s}} = \frac{n\tau(1-\tau)^{n-1}}{P_{\mathrm{tr}}}, \tag{4}$$

$$p = 1-(1-\tau)^{n-1}. \tag{5}$$

Another equation on p and τ is given in Ref. [9] which is derived based on conditional probability

$$\tau = \frac{1}{1 + \frac{1-p}{1-p^{R+1}}\sum_{i=0}^{R} p^i \mathrm{E}[b_i]}, \tag{6}$$

where i is the backoff stage, R is the maximum backoff stage, and E[b_i] is the average value of the backoff counter extracted by a station entering stage i.

Let D be the average access delay, defined as the time elapsing between the instant of time the packet becomes head-of-line (HOL) and the instant of time the packet terminates a successful deliver.

Thanks to Little's theorem

$$D = \frac{\mathrm{E}[N]}{S/\mathrm{E}[P]}, \tag{7}$$

where E[N] represents the average number of competing stations which will successfully deliver their HOL packet.

From the result of Ref. [9], we obtain

$$D = \frac{n}{S/\mathrm{E}[P]} - \mathrm{E[slot]}(1-B_0)\frac{p^{R+1}}{1-p^{R+1}}\sum_{i=0}^{R}(1+\mathrm{E}[b_i]), \tag{8}$$

where E[slot] is the denominator of Eq. (2).

Let E be the total energy consumed by a station. Given that a node (referred to as STAs) has to achieve data transfer of L bits and there are N stations in the network, the energy used by STAs will be

$$E = T_{\mathrm{T}}P_{\mathrm{T}} + T_{\mathrm{R}}P_{\mathrm{R}} + T_{\mathrm{L}}[(1-F_{\mathrm{R}})P_{\mathrm{I}} + F_{\mathrm{R}}P_{\mathrm{R}}], \tag{9}$$

where P_{T}, P_{R} and P_{I} are the power consumption rates during the transmission, reception and idle states of STAs; T_{T} and T_{R} are the time STAs that will spend transmitting frames and receiving frames, respectively; T_{L} is the time STAs that will be listening to a packet transmission going on between two other nodes. When such a transmission between two other nodes is taking place, a fraction (F_{R}) of the packet will be received at STAs before it realizes that the transmission is not meant for itself and switches to idle mode.

The transmission time for the data rate (X Mbit/s) node for a given number of bits L will be

$$T_{\mathrm{T}}(X) = \frac{L}{l}\left(\mathrm{PHYheader} + \frac{\mathrm{MACheader} + l}{X}\right), \tag{10}$$

where X is the data rate of the node. The fraction L/l provides the number of transmissions that the node will have to make to transmit a total of L bits; PHYheader and MACheader are the length of the header of physical layer and MAC packets, respectively. Similarly,

$$T_{\mathrm{L}} = \frac{L}{l}(n-1)[\mathrm{PHYheader} + (\mathrm{MACheader} + l)T_{\mathrm{x}}], \tag{11}$$

and

$$T_{\mathrm{R}} = \frac{L}{l}n\mathrm{Backoff}, \tag{12}$$

where Backoff is the time spent in the random backoff required by 802.11 MAC, and T_{x} is the transmission time of data rate X.

The performance of the proposed protocol is evaluated by an event-driven custom simulator using the MATLAB programming language. In order to compare the performance of ACoopMAC and CoopMAC, we adopt the same parameters used in Ref. [1]. The parameters used in simulation are shown in Table 1. The mobile stations are randomly distributed in a circle with a radius of 100 m, and the access point is located in the center of this circle. Rayleigh fading with unit mean is used to model the wireless channel in a typical environment. The network is under a heavy load condition, and traffic is evenly distributed across all the nodes in the network. Packets arrive to the network at a rate of 500 packets/s according to Poisson distribution.

Table 1 Parameters used in simulation

parameters	value
MACheader	272 bits
PHYheader	192 bits
IRTS	160 bits + PHYheader
IHTS	112 bits + PHYheader
ICTS	112 bits + PHYheader
slot time	20 μs
aCWMin	31 slot time
aCWMax	1023 slot time
retry limit	6

As shown in Fig. 5, both cooperative schemes significantly improve the performance compared to 802.11b with the increasing number of stations. This is because the more stations in the network, the higher possibility that a station can find a helper and transmit at a higher rate. In ACoopMAC, the throughput starts from 2.1 Mbit/s and increases to 3.1 Mbit/s when we have 30 stations, which is much higher than that in CoopMAC. This is due to less overheads and collisions in ACoopMAC. Since the benefits of cooperation are fully utilized, the throughput increase is almost flat with a steady increase in the number of stations.

As we can see from Fig. 6, the system delay of our proposed protocol is less than the delay of legacy 802.11b and CoopMAC.

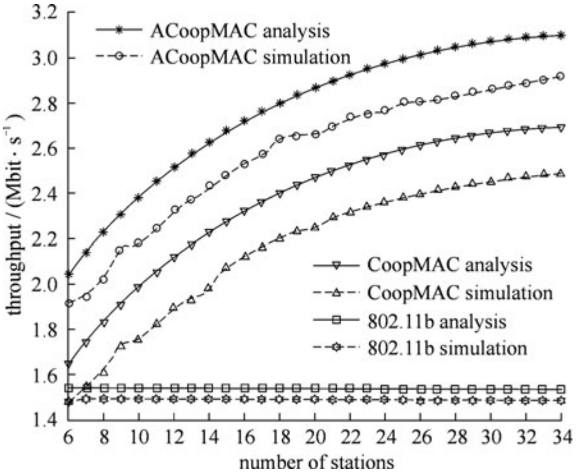

Fig. 5 Throughput (payload = 1024 B) versus number of stations

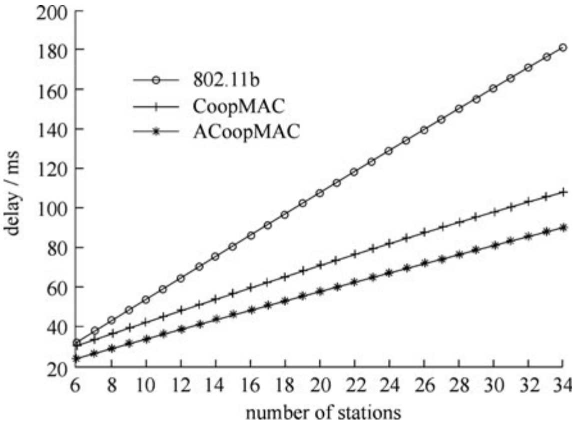

Fig. 6 Delay versus number of stations

The performance of energy consumption is shown in Fig. 7; we can see that the proposed protocol can bring evident energy saving. Since the probability of retransmission increases with the number of stations growing, the energy consumption of 802.11b and CoopMAC gradually increases. However, in our protocol, with the collision probability decreasing, the energy consumption is almost unchanged without maintaining a relay list for each station.

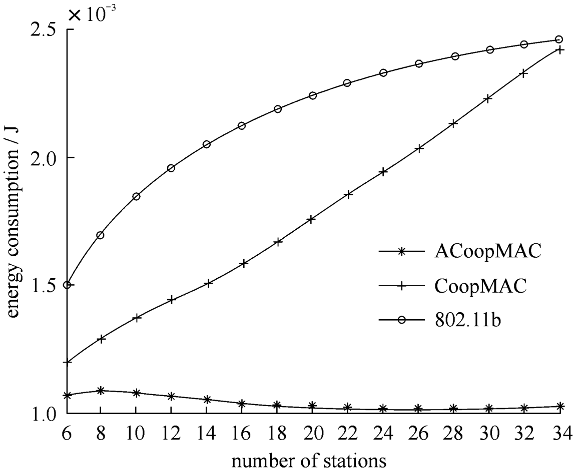

Fig. 7 Energy consuming versus number of stations

As shown in Fig. 8, the throughput of ACoopMAC is almost unchanged with the moving velocity of the stations increasing. It is evident that the proposed scheme is very suitable to the mobility of the stations. This can be explained by the fact that the dynamic relay selection scheme is adopted in ACoopMAC.

5 Conclusions

This paper proposes a novel adaptive cooperative MAC protocol with new frame control formats based on channel feedback, which is completely compatible with the legacy

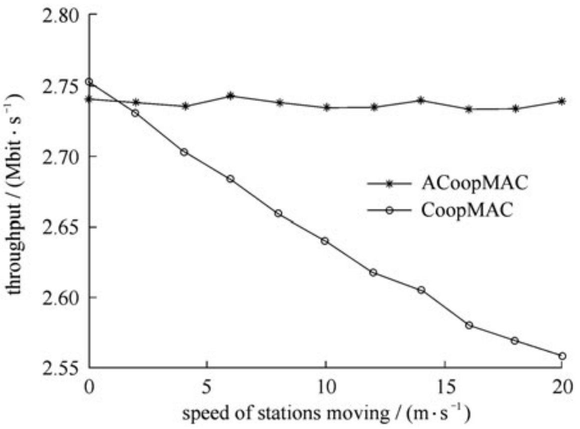

Fig. 8 Impact of mobility (number of stations is 25)

802.11 DCF. To adapt to dynamic channel variation and network topology, the sender adaptively selects a transmission scheme based on the instantaneous channel measurements. The analytical and simulation results show that our proposed protocol outperforms the legacy 802.11b and CoopMAC proposed in literature.

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