Research Article

A CSMA Mechanism with Variable Collision Control and Priority Provision in Multichannel Mobile Ad Hoc Networks

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Toward making the conventional carrier sense multiple access (CSMA) protocol transmit and control mobile ad hoc network systems, as well as reducing energy consumption, an adaptive multichannel multipriority two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms (iCSMA for short) is proposed. Based on the conventional two-slot model of the CSMA protocol, iCSMA introduces a concept of collision duration (b), which divides the system's timeslot into the duration of successful packet transmission ($1 + a$), the duration of collision ($b + a$), and the duration of the idle state (a) of the system. By employing iCSMA, the loss of the system could be reduced with a fine-tuned collision duration (b), which leads to improved performance compared to the conventional 1P-persistent CSMA protocol. Furthermore, a three-way handshake mechanism is introduced for monitoring the entire network system at a minimal cost of throughput. Toward a higher channel utilization rate, a multichannel and multipriority function is employed in the implementation of multiservice communication for the system. Besides, with an adaptive mechanism, the transmission probabilities p_1 and p_2 are reasonably set so that the system will not produce a complete collision under the condition of high load, and the throughput can also be stabilized. Based on the battery model, the lifetime of the system nodes (T) is extended. Both theoretical analysis and experimental results confirm the accuracy of the theoretical derivation.

1. Introduction

A mobile ad hoc network (MANET) refers to a wireless mobile node system that can freely and dynamically self-organize into arbitrary, temporary network topology and allow people and equipment to seamlessly network in areas without any preset communication infrastructure [1, 2]. Simultaneously, a MANET refers to one kind of mobile network encompassing the wireless mobile nodes for communication [3]. It is an ad hoc network composed of a group of wireless mobile nodes without any central entity as shown in Figure 1. When the organization network is deployed, there is no need to rely on the existing fixed communication network infrastructure. Between mobile nodes, with the support of various protocols designed in advance, the wireless channels rely on the cooperation between nodes to cooperate with each other. Each mobile node

is supported by various protocols designed in advance and depends on the mutual cooperation between nodes. In the mobile, complex, and changing wireless environment, it forms a network by itself. With the help of multihop transmission technology, it can make up for the limited transmission distance of wireless devices. Thereby, it can expand the coverage of the network and provide various services and transmission of various services for users. Finally, it enables sharing of information and services [4, 5]. Mobile ad hoc wireless networks possess highly constrained energy resources. The available energy resources should thus be used efficiently in order to satisfy the requirements. Hence, the protocols at all layers of the protocol stack should be energy aware and energy efficient [6, 7].

The energy consumption of mobile ad hoc networks is often inseparable from the throughput [8, 9], collision rate, and idle rate of system nodes. Thus, improving the

FIGURE 1: The typical structure of a MANET.

throughput, collision rate, and idle rate of the system through the improvement of the transmission protocol has become the key to solving this problem. There is some existing research for conventional random multiple access communication protocols. Literature [10] proposed a demand-assigned multiaccess (DAMA) time-division multiple access (TDMA) system with a remainder-based contention-avoidance scheme. In our scheme, the wireless users are divided into several groups according to the available transmission opportunities in each time frame, and each user sends its bandwidth request during the time window for its group. According to the average collision probability and the utilization of the transmission opportunities in the last two rounds of contention resolution, the size of available transmission opportunities and the number of wireless users who issue bandwidth requests are adaptively controlled by the base station and the wireless users, respectively. Bellalta et al. [11] analyzed the interactions between a group of neighboring WLANs that use channel bonding and evaluate the impact of those interactions on the achievable throughput. A continuous-time Markov network model that is able to capture the coupled dynamics of a group of overlapping WLANs is introduced and validated. Lu et al. [12] improved the existing random multiple access protocol and designs the 1-persistent CSMA (Carrier Sense Multiple Access) protocol with the variable collision length (1P-CSMA (b)). At the same time, considering the different requirements of different video services, multipriority 1-persistent CSMA random multiple access control protocol with variable collision length is proposed, which sets different priorities and then competes fairly. Xu et al. [13] proposed a multipriority dual-clock probability detection CSMA (MPDCPD-CSMA) protocol with a monitoring mechanism based on the characteristics of wireless network nodes and combining multiple hybrid control strategies.

The conventional CSMA protocol normalizes both the transmission success and the collision timeslot length to 1, and so it is not considered that when the information packet collides, the collision duration can be changed by cutting off the transmission. This thereby causes the problems of low throughput and high collision rate with the system. In the end, it will cause serious problems such as higher energy consumption of the system. At the same time, when the

system is under a high load, the conventional CSMA protocol will cause a complete collision status, which will cause the system to be unable to successfully transmit a message packet. In terms of the questions, an adaptive multichannel multipriority two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms (AMMJ-CSMA/RCAB) in mobile ad hoc networks is proposed in this paper. It controls the whole process of the system by controlling the collision length b and sending probabilities p_1 and p_2 . At the same time, a multichannel and multipriority mechanism is introduced to speed up the information transmission rate and improve the system utilization rate as shown in Figure 2. Furthermore, through the adaptive mechanism, the transmission probabilities p_1 and p_2 are reasonably set so that the system will not produce a complete collision under the condition of high load, and the throughput can also be stabilized. Finally, by analyzing the energy efficiency of the system, the receiving energy consumption, transmission energy consumption, and idle energy consumption of the mobile ad hoc network communication system are obtained. The lifetime of the system node [14, 15] is used as an indicator to reflect whether the power consumption of the system has improved. It can be determined through simulation experiments that the lifetime of the system nodes has been significantly extended.

2. Analysis of Performance

2.1. The Theory of the iCSMA Protocol. In the mobile ad hoc communication system [16, 17], the terminals in the communication channel of the system need to listen to the state of the communication channel before sending information packets. When the communication channel of the system is idle, the communication channel is controlled by using a persistent multiple access protocol of 1 at the beginning of the next timeslot. When the communication channel is busy, the transmission timeslot is normalized as $(1 + 2a)$. When the information packet arrives within the transmission slot $(1 + 2a)$, the random multiple access protocol of probability detection is used to control the communication channel. To allow the transmission probability to fully adapt to different states of the site, different transmission probabilities are set

FIGURE 2: The multichannel and multipriority model.

according to the time when the information packet arrives. When the information packet arrives within transmission slot 1, the probability p_1 is used to decide whether to send the information packet at the beginning of the next timeslot, and the probability $(1 - p_1)$ is used to determine to continuously listen to the state of the communication channel. When the information packet arrives within a two-way propagation timeslot $2a$, the probability p_2 is used to decide to send the information packet at the beginning of the next timeslot, and the probability $(1 - p_2)$ is used to determine to continuously listen to the state of the communication channel. At the same time, before each information packet that needs to be transmitted, they first communicate through a short handshake frame RTS/CTS. After other unrelated nodes receive the handshake frame RTS/CTS, they suppress their own sending actions to avoid sending collisions after that. Then, a monitoring information segment (ACK/NAK) is added to the end of each information packet that needs to be transmitted. The information packet needs to be acknowledged through using ACK when it is received correctly, and the information packet needs to be acknowledged through using NAK when a collision occurs. Finally, when the information packets collide, the transmission will be truncated after a certain timeslot length. This strategy can effectively improve the throughput of the communication channel. After passing the handshake protocol, it can provide a short “headroom” for the information transmission between the terminals. Thereby, it can reduce the probability of sending collisions. After adding a monitoring information segment, the system can acquire a certain understanding of the information packets and the state of the communication channel. Thus, it serves the role of supervising the communication channel. Finally, it can effectively bring the system to a balanced state.

Based on the conventional 1-persistent CSMA protocol model and the two-dimensional probability CSMA protocol model, this paper proposes a three-slot model of 1-persistence and two-dimensional probability joint control under the variable collision duration and three-way handshake mechanism, as shown in Figure 3. The following assumptions about its mathematical model are first made:

- (i) The access methods of the system nodes are based on a random multiple access protocol that adheres to the joint control of 1P-CSMA and two-dimensional

probability CSMA. The information packet arrival process of each station on the communication channel is independent and obeys the $(0, 1)$ distribution. When the number of points is sufficient (greater than 20), the distribution on the communication channel is similar to the Poisson distribution (the parameter is G_i).

- (ii) The number of users on the communication channel is according to the Poisson flow.
- (iii) It is assumed that the communication channel is in an ideal state without noise interference.
- (iv) When two or more information packets collide in the communication channel at the same time, the information packets will be retransmitted in a certain timeslot, and this will not affect the arrival process of the communication channel.
- (v) The normalized value of the successful transmission (U) length of the information packet is 1. The collision duration of the information packet collision (B) is b . The busy state (BU) of the information packet is composed of the successful (U) and the collision (B) transmission. The length of time in which the channel is in the idle state (I) is indicated by a . The transmission periods (TP) of successful transmission and collision transmission are $(1 + 2a)$ and $(b - 2a)$, respectively.

Before establishing the mathematical model and analyzing the protocol, the corresponding variables need to be explained, as shown in Table 1.

The probability $P(W(t) = n)$ that n information packets arrive in channel i during time t is

$$P(W(t) = n) = \frac{(G_i t)^n}{n!} e^{-G_i t}. \quad (1)$$

The probability $P(K_1(t) = m)$ that m of the n packets arriving in channel i within time t are sent in the 1-persistent manner is

$$P(K_1(t) = m) = P(W(t) = m) = \frac{(G_i t)^m}{m!} e^{-G_i t}. \quad (2)$$

The probability $P(K_2(t) = m)$ that m of the n packets arriving in channel i within time t are sent in the p -persistent manner is

$$\begin{aligned} P(K_2(t) = m) &= \sum_{n=m}^{\infty} P(W(t) = n) C_n^m p^m (1-p)^{n-m} \\ &= \frac{(G_i p t)^m}{m!} e^{-G_i p t}. \end{aligned} \quad (3)$$

The probability q_a^0 that no information packet arrives and the probability q_a^1 that only one information packet arrives during a certain idle timeslot a are, respectively,

$$\begin{aligned} q_a^0 &= P(K_1(a) = 0) = e^{-G_i a}, \\ q_a^1 &= P(K_1(a) = 1) = G_i a e^{-G_i a}. \end{aligned} \quad (4)$$

FIGURE 3: The iCSMA protocol model in mobile ad hoc networks.

TABLE 1: Variables in the mathematical models.

Variable symbol	Variable meaning
$W(t)$	Channel i has n packets of information within time t
$K_1(t)$	m of the n packets arriving in channel i within time t are sent in the 1-persistent manner
$K_2(t)$	m of the n packets arriving in channel i within time t are sent in the P-persistent manner
q_a^0	Probability that no information packet arrives in a certain idle timeslot a
q_a^1	Probability that an information packet arrives in a certain idle timeslot a
$q_{(1+2a)}^0$	Probability that no information packet arrives in a certain transmission cycle $(1 + 2a)$
$q_{(1+2a)}^1$	Probability that an information packet arrives in a certain transmission cycle $(1 + 2a)$
N_U	The number of transmission cycles used to send successful events in a busy period
N_{BU}	Total number of transmission cycles included in a busy cycle
$P\{N_{BU} = j\}$	Probability distribution function of j compound events BU occurring consecutively in a busy period
$P\{N_I = i\}$	Probability distribution function of i idle events I occurring continuously in a cycle joint probability distribution function of i compound events BU and j idle events I occurring consecutively in a cycle
$e(U)$	Average length of the total number of packets successfully sent in a busy period in the last timeslot a of the idle period, only one information packet arrives, and the average length of information packets when the first timeslot a of the transmission period TP is successfully transmitted
$e(U_2)$	The average length of information packets when only one information packet arrives during the transmission period TP and the information packet is sent successfully
$e(BU)$	Average length of the total number of successful packets and collision packets sent during a busy period
$e(U_{BU})$	The average length of successful transmissions during a busy period (including delay)
$e(B_{BU})$	Average length of collisions during a busy period (including delay)
$e(I_1)$	Average length of idle periods during a cycle
$e(M)$	The average length of the three-way handshake mechanism during a transmission cycle
$e(T_i)$	The average length of transmission cycles
S_U	Throughput
S_B	Collision
S_I	Idle rate in a broad sense
S_{I_1}	Idle rate
S_M	Loss rate of three-way handshake mechanism

The probability $q_{(1+2a)}^0$ that no information packet arrives and the probability $q_{(1+2a)}^1$ that only one information packet

arrives during a certain transmission cycle $(1 + 2a)$ are, respectively,

$$\begin{aligned}
 q_{(1+2a)}^0 &= P(K_2(t = 1|p = p_1) = 0) \times P(K_2(t = 2a|p = p_2) = 0) = e^{-G_i(p_1 + 2ap_2)}, \\
 q_{(1+2a)}^1 &= P(K_2(t = 1|p = p_1) = 0) \times P(K_2(t = 2a|p = p_2) = 1) \\
 &\quad + P(K_2(t = 1|p = p_1) = 1) \times P(K_2(t = 2a|p = p_1) = 0) = G(p_1 + 2ap_2)e^{-G(p_1 + 2ap_2)}.
 \end{aligned} \tag{5}$$

Therefore, it can be determined that the probability $P(N_I = i)$ of consecutive i idle events I and the

probability $P(N_{BU} = j)$ of consecutive j busy events BU are

$$P(N_I = i) = (e^{-G_i a})^{i-1} (1 - e^{-G_i a}),$$

$$P(N_{BU} = j) = e^{-G_i (p_1 + 2ap_2)} \left(1 - e^{-G_i (p_1 + 2ap_2)}\right)^{j-1}. \quad (6)$$

Therefore, in a cyclic period T_i , the joint probability distribution of i consecutive idle events I and j consecutive busy events BU is

$$P\{N_I = i, N_{BU} = j\} = (e^{-G_i a})^{i-1} (1 - e^{-G_i a}) e^{-G_i (p_1 + 2ap_2)} \left(1 - e^{-G_i (p_1 + 2ap_2)}\right)^{j-1}. \quad (7)$$

It can be deduced that when the communication channel is idle in a cyclic period T_i , the average number of timeslots $e(N_{I_1})$, the average idle length $e(I_1)$, and the average compound time $e(N_{BU})$ are

$$e(N_{I_1}) = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} iP(N_I = i, N_{BU} = j) = \frac{1}{1 - e^{-G_i a}}, \quad (8)$$

$$e(I_1) = a \times e(N_{I_1}) = \frac{a}{1 - e^{-G_i a}}, \quad (9)$$

$$e(N_{BU}) = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} jP(N_I = i, N_{BU} = j) = \frac{1}{e^{-G_i (p_1 + 2ap_2)}}. \quad (10)$$

Analyzing successful events I , events can be divided into two categories. The first type of event, U_1 , is where some information packets arrive in the last timeslot a of the consecutive i idle periods of the communication channel, but only one information packet is determined to be transmitted with probability p_1 , and the packet will be successfully transmitted in the next timeslot. Other information packets are still waiting, thus avoiding sending collisions. The second type of event, U_2 , is where some information packets arrive in a certain busy period and are the only ones that exist in the communication channel. If an information packet arrives in timeslot 1, it is sent in the manner of 1-persistence. If an information packet arrives within the timeslot $2a$, it is determined to be transmitted with probability p_2 . Therefore, the information packet will

be successfully transmitted in the next transmission cycle TP.

Based on the above, the proportion of the average number of the event timeslots (that is, when there is only one information packet) is

$$e(N_{U_1}) = \frac{q_a^1}{1 - q_a^0} = \frac{G_i a e^{-G_i a}}{1 - e^{-G_i a}}, \quad (11)$$

and the average number of the event timeslots is $e(N_{U_2})$, that is, the number of transmission timeslots occupied by sending successful events U in a busy period. Combined with the definition of the protocol and based on the time when the only information packet arrives, the choice of sending in the 1-persistence mode or the probability p_2 detection mode in the busy cycle is determined. Supposing that there are $N_{BU} = n$ transmission periods TP in a busy period BU, the number of successful events U_2 is sent to satisfy the binomial distribution $B(n, q_{(1+2a)}^1)$; that is,

$$e(N_{U_2} | N_{BU} = n) = n q_{(1+2a)}^1. \quad (12)$$

Assuming that there are n transmission periods TP in a busy period BU, and combined with the meaning of the binomial distribution, the average number of the event timeslots $e(N_{U_2})$ is the expected value of the number of successful events U_2 :

$$e(N_{U_2}) = e(e(N_{U_2} | N_{BU} = n)) = e(N_{BU} q_{(1+2a)}^1) = q_{(1+2a)}^1 e(N_{BU}). \quad (13)$$

Therefore,

$$e(N_{U_2}) = q_{(1+2a)}^1 e(N_{BU}) = \frac{G_i (p_1 + 2ap_2) e^{-G_i (p_1 + 2ap_2)}}{e^{-G_i (p_1 + 2ap_2)}} = G_i (p_1 + 2ap_2). \quad (14)$$

Thus, in a cyclic period T_i , the average number of timeslots for which packets are successfully sent $e(N_U)$ and the average number of timeslots for which collisions occur $e(N_B)$ are

$$e(N_U) = e(N_{U_1}) + e(N_{U_2}) = \frac{G_i a e^{-G_i a}}{1 - e^{-G_i a}} + G_i (p_1 + 2ap_2),$$

$$e(N_B) = e(N_{BU}) - e(N_U) = \frac{(1 - e^{-G_i a}) \left[1 - G_i (p_1 + 2ap_2) e^{-G_i (p_1 + 2ap_2)}\right]}{e^{-G_i (p_1 + 2ap_2)} (1 - e^{-G_i a})} \cdot \frac{-G_i a e^{-G_i (a + p_1 + 2ap_2)}}{e^{-G_i (p_1 + 2ap_2)} (1 - e^{-G_i a})}. \quad (15)$$

Therefore, it can be found that, within a cyclic period T_i , the effective average time of successful transmission $e(U)$, the effective average time of collision $e(B_{BU})$, and the

effective average time lost by the three-way handshake mechanism $e(M)$ are

$$\begin{aligned}
 e(U) &= e(N_U) \cdot 1 = \frac{G_i a e^{-G_i a}}{1 - e^{-G_i a}} + G_i (p_1 + 2ap_2), \\
 e(B) &= e(N_B) \cdot b = \frac{b \cdot \left\{ (1 - e^{-G_i a}) \left[1 - G_i (p_1 + 2ap_2) e^{-G_i (p_1 + 2ap_2)} \right] - \frac{-G_i a e^{-G_i (a + p_1 + 2ap_2)}}{(1 - e^{-G_i a})} \right\}}{e^{-G_i (p_1 + 2ap_2)}}, \\
 e(M) &= e(N_{BU}) \cdot (2a + \tau_R + \tau_C + \tau_A) = \frac{(2a + \tau_R + \tau_C + \tau_A)}{e^{-G_i (p_1 + 2ap_2)}}.
 \end{aligned} \tag{16}$$

Thus, it can be inferred that within a cyclic period, the average duration of successful transmission $e(U_{BU})$, the average duration of collisions $e(B_{BU})$, and the average

duration of composite events $e(BU)$ (including delay) in the composite event BU are

$$\begin{aligned}
 e(U_{BU}) &= e(N_U) \cdot (1 + 2a + \tau_R + \tau_C + \tau_A) \\
 &= \frac{G_i a (1 + 2a + \tau_R + \tau_C + \tau_A) e^{-G_i a}}{1 - e^{-G_i a}} + G_i (p_1 + 2ap_2) (1 + 2a + \tau_R + \tau_C + \tau_A),
 \end{aligned} \tag{17}$$

$$\begin{aligned}
 e(B_{BU}) &= e(N_B) \cdot (b + 2a + \tau_R + \tau_C + \tau_A) \\
 &= (b + 2a + \tau_R + \tau_C + \tau_A) \cdot \left(1 - e^{-G_i a} \right) \cdot \left\{ \frac{\left[1 - G_i (p_1 + 2ap_2) e^{-G_i (p_1 + 2ap_2)} \right] - G_i a e^{-G_i (a + p_1 + 2ap_2)}}{e^{-G_i (A + 2ap_2)} (1 - e^{-G_i a})} \right\}, \\
 e(BU) &= e(U_{BU}) + e(B_{BU}) \\
 &= \frac{G_i a (1 - b) e^{-G_i (a + p_1 + 2ap_2)}}{e^{-G_i (p_1 + ap_2)} (1 - e^{-G_i a})} \\
 &\quad + \frac{(1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2) (1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{e^{-G_i (p_1 + ap_2)} (1 - e^{-G_i a})}.
 \end{aligned} \tag{18}$$

Therefore, it can be obtained that the average duration of a system $e(T_i)$ in a certain transmission cycle T_i is

$$\begin{aligned}
 e(T_i) &= e(I_1) + e(BU) \\
 &= \frac{G_i (p_1 + 2ap_2) (1 - b) e^{-G_i (p_1 + 2ap_2)}}{e^{-G_i (p_1 + 2ap_2)}} + \frac{(2a + b + \tau_R + \tau_C + \tau_A) + [G_i a (1 - b) e^{-G_i a} + a]}{(1 - e^{-G_i a})}.
 \end{aligned} \tag{19}$$

Thus, it can be obtained that the throughput S_U , collision S_B , idle rate S_{I_1} , and loss rate of the three-way handshake mechanism S_M of the system are

$$S_U = \frac{e(U)}{e(T_i)} = \frac{[G_i a e^{-G_i a} + G_i (p_1 + 2ap_2)(1 - e^{-G_i a})] e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{1 + [G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}, \quad (20)$$

$$S_B = \frac{e(B)}{e(T_i)} = \frac{b \cdot \left\{ (1 - e^{-G_i a}) \left[1 - G_i (p_1 + 2ap_2) e^{-G_i (p_1 + 2ap_2)} \right] - G_i a e^{-G_i (a + p_1 + 2ap_2)} \right\} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{1 + [G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]},$$

$$S_{I_1} = \frac{e(I_1)}{e(T_i)} = \frac{a e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{1 + [G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]},$$

$$S_M = \frac{e(M)}{e(T_i)} = \frac{(2a + \tau_R + \tau_C + \tau_A)(1 - e^{-G_i a}) / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{1 + [G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}. \quad (21)$$

2.2. The Multichannel and Multipriority Mechanism. Mobile ad hoc communication systems are often composed of multiple channels [18–20]. The system nodes set different priorities according to different service requirements. Each priority has no limit with respect to the number of terminals. The priority is set from low to high as priority 1, ..., priority k , ..., and priority N . Among them, the service on priority i occupies the previous i communication channel; that is, priority 1 occupies communication channel 1, priority 2 occupies communication channel 1 and communication channel 2, ..., and priority i occupies communication channel No.1 to the communication channel No. i [21]. When all N communication channels are occupied, the cyclic occupation starts again from communication channel No.1.

According to the principle of load balancing [22] and the analysis of the above system parameters, for the N communication channel $G_1 = \dots = G_i = \dots = G_N = G$, it can be obtained that the throughput of the system S in the multiple communication channels of the mobile ad hoc communication systems is

$$S = \sum_{i=1}^N \frac{e(U)}{e(I_1) + e(BU_i)}. \quad (22)$$

Therefore, it can be obtained that the throughput S of the system under the two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms is

$$S = N \cdot \frac{(1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{1 + [G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)} / (1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}. \quad (23)$$

The arrival rate of system services with known priority k on communication channel i is $\lambda_k^{p_i}$. According to the above analysis, based on the two-dimensional probability detection and 1-stick joint control

strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms, the throughput S_{pi} of system services with priority k is

$$S_{pi} = \left(\sum_{i=1}^k \frac{1}{N-i+1} \right) \cdot \frac{[G_i a e^{-G_i a} + G_i (p_1 + 2ap_2)(1 - e^{-G_i a})] e^{-G_i (p_1 + 2ap_2)}}{(1 - e^{-G_i a}) [(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)}]} \quad (24)$$

$$1 + \frac{[G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)}}{(1 - e^{-G_i a}) [(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)}]}.$$

2.3. Adaptive Mechanism. According to formula (19), based on the two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms, when the timeslots a and b of the system length are constant, the throughput S_U of the system is nonlinearly related to the arrival rate G_i of information packets, along with the transmission probabilities p_1 and p_2 . We can determine

$$S_U = f(G_i, p_1, p_2). \quad (25)$$

The arrival rate G_i of the information packet is determined by the number of tasks sent by the terminal, which is an uncontrollable factor in the system communication channel. However, the conventional sending probabilities p_1

and p_2 that artificially set probability values are controllable variables. If the transmission probabilities p_1 and p_2 are set to a fixed value, this will cause the system node to properly adjust the transmission, or not, of the information packet according to the state of the communication channel, so that when the communication channel is under a high load, a complete collision will be caused in the communication channel, and any information packet will not be sent successfully. This is not what we expected. In view of the above problems, this paper proposes adaptive transmission probabilities p_1 and p_2 . The transmission probability can be appropriately adjusted according to the arrival rate of the information packet, so that the communication channel tends to be stable and no full collision occurs [23, 24].

According to formula (19),

$$\lim_{G_i \rightarrow \infty} G_i a e^{-G_i a} = 0, \quad (26)$$

$$\begin{aligned} \lim_{G_i \rightarrow \infty} S_U &= \lim_{G_i \rightarrow \infty} \frac{[G_i a e^{-G_i a} + G_i (p_1 + 2ap_2)(1 - e^{-G_i a})] e^{-G_i (p_1 + 2ap_2)}}{1 + [G_i a (1 - b) e^{-G_i a} + a] e^{-G_i (p_1 + 2ap_2)}} \cdot \frac{[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)}]}{[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2)(1 - b) e^{-G_i (p_1 + 2ap_2)}]} \\ &= \lim_{G_i \rightarrow \infty} \frac{G_i (p_1 + 2ap_2) e^{-G_i (p_1 + 2ap_2)}}{(2a + b + \tau_R + \tau_C + \tau_A) + [G_i (p_1 + 2ap_2)(1 - b) + a] e^{-G_i (p_1 + 2ap_2)}}. \end{aligned} \quad (27)$$

In combination with the above, it is known that, in order to prevent the communication channel from completely colliding under the condition of extremely high load, the transmission probabilities p_1 and p_2 must be set to changing adaptive values related to the arrival rate of the information packet. In the case that the throughput of the communication channel is guaranteed to be as large as possible, and the conditions of the transmission probabilities p_1 ($0 < p_1 \leq 1$) and p_2 ($0 < p_2 \leq 1$) are met, it may be assumed that

$$p_1 G_i = p_{1k} G_k |_{\max(S_U)}, \quad (28)$$

$$p_2 G_i = p_{2k} G_k |_{\max(S_U)}. \quad (29)$$

Among them, p_{1k} , p_{2k} , and G_k are the transmission probabilities p_1 and p_2 and the arrival rate G_i of the

information packets on communication channel i with the maximum throughput. Thus,

$$\begin{aligned} p_{1k} G_k |_{\max(S_U)} &= \gamma_1, \\ p_{2k} G_k |_{\max(S_U)} &= \gamma_2. \end{aligned} \quad (30)$$

Substituting equations (28) and (29) into equations (26) and (27), respectively, gives

$$\begin{aligned} p_1 &= \frac{1}{\gamma_1 \cdot G_i}, \\ p_2 &= \frac{1}{\gamma_2 \cdot G_i}. \end{aligned} \quad (31)$$

To obtain the maximum value of the throughput S_U under limited conditions, it is necessary to find the partial

derivative of the arrival rate of the variable information packet G_i , along with transmission probabilities p_{1_k} and p_{2_k} :

$$\text{cond} \begin{cases} G_i \geq 0, \\ p_{1_k} (0 < p_{1_k} \leq 1), \\ p_{2_k} (0 < p_{2_k} \leq 1), \end{cases} \quad (32)$$

$$\begin{cases} f'_{G_i}(G_i, p_{1_k}, p_{2_k}) = 0, \\ f'_{p_{1_k}}(G_i, p_{1_k}, p_{2_k}) = 0, \\ f'_{p_{2_k}}(G_i, p_{1_k}, p_{2_k}) = 0. \end{cases} \quad (33)$$

By using the multivariate function to find the maximum value, it can be determined that, under the condition of $a = 0.1$ and $b = 0.1$ and the limit of formula (32), when the maximum value $S_U = f(G_i, p_{1_k}, p_{2_k})$ is obtained, there are multiple solutions for the packet arrival rate G_i and transmission probabilities p_{1_k} and p_{2_k} , respectively. Considering the nature of formula (19), we might as well take

$$\begin{cases} G_i = G_{\min}|_{\max}(s_v), \\ p_{1_k} = \frac{p_1 + 2ap_2}{2}|_{\max}(s_v), \\ p_{2_k} = \frac{p_1 + 2ap_2}{4a}|_{\max}(s_v). \end{cases} \quad (34)$$

Thus, when the maximum value $S_U = f(G_i, p_{1_k}, p_{2_k})$ is reached, the arrival rate G_i and transmission probabilities p_{1_k} and p_{2_k} of the information packet are

$$\begin{cases} G_i = G_{\min}|_{\max}(s_v) = 6.3605 \\ p_{1_k} = \frac{p_1 + 2ap_2}{2}|_{\max}(s_v) = 0.05, \\ p_{2_k} = \frac{p_1 + 2ap_2}{4a}|_{G_{\min}(s_v)} = 0.25 \\ \gamma_1 = \frac{1}{G_{\min} \times p_{1_k}} = 0.3144 \\ \gamma_2 = \frac{1}{G_{\min} \times p_{2_k}} = 0.6289 \end{cases} \quad (35)$$

In summary, the adaptive values of the transmission probabilities p_1 and p_2 are

$$\begin{aligned} p_1 &= \begin{cases} 0.1 & G_i < 6.3605 \\ \frac{1}{3.1444 \times G_i} & G_i \geq 6.3605 \end{cases}, \\ p_2 &= \begin{cases} 0.1 & G_i < 6.3605 \\ \frac{1}{0.6289 \times G_i} & G_i \geq 6.3605 \end{cases} \end{aligned} \quad (36)$$

2.4. Analyzing Delay. Before analyzing the delay [25, 26], it is assumed that the ACK/NCK signal can always be transmitted correctly. Assuming that R is the average time extension of the information packet retransmission and that R is the average delay of one information packet in the communication channel when it is sent twice in a row, then R is composed of the following parts: the information packet transmission timeslot length 1, two-way propagation delay $2a$, the requested time of the information packet transmission τ_R , the response time of the information packet transmission τ_C , the transmission time of the ACK/NCK signal $\tau_A = \tau_N = \tau$, and the delay of average retransmission σ . Therefore, it can be obtained that the average timeslot length R of the information packet retransmission is

$$R = 1 + 2a + \tau_R + \tau_C + \tau + \delta. \quad (37)$$

Among them, the average number of information packets to be retransmitted is $(G/S - 1) \cdot R$, so that the average transmission delay (ATD) of the information packets is

$$\text{ATD} = \left(\frac{G}{S} - 1 \right) \cdot R + 1 + 2a + \tau_R + \tau_C + \tau. \quad (38)$$

According to the throughput formula (27) and the average transmission delay formula (38) of the information packet, it can be obtained that, based on the two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms, the average delay ATD of the information packet in channel i is

$$\begin{aligned} \text{ATD} &= \left(\frac{(1 - e^{-G_i a}) \left[(2a + b + \tau_R + \tau_C + \tau_A) + G_i (p_1 + 2ap_2) (1 - b) e^{-G_i (p_1 + 2ap_2)} \right]}{[ae^{-G_i a} + (p_1 + 2ap_2)(1 - e^{-G_i a})] e^{-G_i (p_1 + 2ap_2)}} + \frac{[G_i a (1 - b) e^{-G_i a} + a]}{[ae^{-G_i a} + (p_1 + 2ap_2)(1 - e^{-G_i a})] e^{-G_i (p_1 + 2ap_2)} - 1} \right) \cdot R + \\ &1 + 2a + \tau_R + \tau_C + \tau. \end{aligned} \quad (39)$$

2.5. Analyzing Energy Effectiveness. In the mobile ad hoc network system, the system node is mainly composed of two parts: a network communication system and a processing system. The network communication system is mainly responsible for receiving and sending data, and the processing system mainly performs data processing. Both parts will generate energy consumption during data transmission [27]. The energy consumed by the network communication system is much larger than that of the processing system, and the energy consumed by data processing is relatively small. In the mobile ad hoc network system, the system nodes mainly have four working modes, receive, send, idle, and sleep, and their energy consumption decreases in that order. However, when the system node is in an idle state, it needs to listen to the state of the communication channel at all times and operate on the received information packets. Therefore, when the system node is in an idle state, the mobile ad hoc network will also generate significant energy consumption. In contrast, when a system node is in a sleep state, the node does not need to perform receiving, sending, and listening actions, and so the energy consumption is very low [28]. In view of the above problems, it is assumed that the energy consumption of the system nodes in the sleep state and the energy consumption of the processing system are negligible. This article primarily analyzes the receiving energy consumption, transmission energy consumption, and idle energy consumption of the mobile ad hoc network communication system.

Aiming at the above energy consumption problem, this paper proposes an adaptive two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms to effectively reduce energy consumption. On this basis, the energy consumption problem of the protocol is analyzed by introducing the power problem of communication channel detection. It is assumed that the power of the system node in the transmission state is $P_{TS} = 1.8 \text{ mW}$, the power in the reception state is $P_{RS} = 9 \text{ mW}$, and the power of the communication channel in the idle state is $P_{IS} = 0.5 \text{ mW}$. The energy consumption under the three-way handshake mechanism is negligible.

2.5.1. Receiving Energy Consumption. The energy consumed by a system node in the receiving mode is the energy consumed W_{RE} by successfully receiving information packets within a cyclic period T_i :

$$W_{RC} = e(U)P_{RS} = 0.9 \times \left[\frac{G_i a e^{-G_i a}}{1 - e^{-G_i a}} + G_i (p_1 + 2ap_2) \right] (\text{mW}). \quad (40)$$

2.5.2. Transmission Energy Consumption. In a busy period, when an information packet arrives in transmission slot 1, it is determined with probability p_1 to send the information packet at the beginning of the next timeslot, and it is determined with probability $(1 - p_1)$ to continuously listen to

the communication channel state. When the communication channel is idle, the average number of information packets sent at the beginning of the next transmission cycle is Gp_1 . When an information packet arrives in a two-way propagation slot $2a$ and the communication channel is detected to be idle, the probability p_2 is used to determine that the average number of information packets sent at the beginning of the next slot is $2aGp_2$, and the number of transmission cycles of the communication channel within one period is $(e(N_{BU}) - 1)$. In the idle period, when the information packet arrives in the last timeslot of the idle period, and the next transmission cycle sends data in the manner of the 1P-CSMA protocol, the average number of information packets sent in the first slot of the transmission cycle is Ga .

According to the above, the transmission energy consumption W_{TE} within one cycle T_i of the communication channel is

$$W_{TE} = P_{TS}(Gp_1 + 2aGp_2)[e(N_{BU}) - 1] + P_{TS}Ga. \quad (41)$$

2.5.3. Idle Energy Consumption. During the busy period, the average time for the information packet node to listen to the communication channel during transmission timeslot 1 is $(2a + 0.5)Gp_1$, and the average time for the information packet node to listen to the communication channel during transmission timeslot $2a$ is $2Gp_2a^2$. The number of transmission cycles of a communication channel in one cycle is $e(N_{BU})$. Therefore, the total time $t_I(BU)$ that all system nodes need to listen during the busy period of the communication channel is

$$t_I(BU) = e(N_{BU})[(2a + 0.5)Gp_1 + 2Gp_2a^2]. \quad (42)$$

However, the total time $t_I(I)$ that all system nodes need to listen during the idle period of the communication channel is

$$t_I(I) = \frac{1}{2}Ga^2e(N_{I}). \quad (43)$$

It can be determined that the idle energy consumption W_{IE} in a cycle T_i is

$$W_{IE} = [t_I(BU) + t_I(I)]P_{IS}. \quad (44)$$

To summarize, the average power P_i of the communication channel i is

$$P_i = \frac{W_{RE} + W_{TE} + W_{IE}}{e(T_i)}. \quad (45)$$

Second, the lifetime of the system nodes is also an important indicator of the energy efficiency of a mobile ad hoc network system [29]. According to [30], a simplified version of the battery model is designed. Assuming that the voltages before and after the use of an LR03 battery are $U_1 = 1.5 \text{ V}$ and $U_2 = 0.9 \text{ V}$, the average voltage is $\bar{U} = 1.2 \text{ V}$, and the battery capacity is set to $C = 1.3 \text{ A} \times \text{h}$. If the battery duration is $T(h)$, then the total energy E of the battery is

$$E = \text{UIT} = \text{UC} = 1.2 \text{ V} \times 1.3 \text{ A} \times h = 1.56 \text{ W} \times h. \quad (46)$$

Considering the problem of energy leakage during the use of the battery, it is determined by measuring the battery vacancy for one year that the energy leaked in one year is approximately 10% of the total energy, and its loss power P_{LK} is

$$P_{\text{LK}} = \frac{E \times 10\%}{24 \times 365} \text{ W}. \quad (47)$$

If the average power of the system node is $\bar{P}$ W when the battery power is exhausted, the lifetime T (year) of the system node is

$$\bar{P} = \frac{1.8e(U_{\text{BU}}) + 9e(B_{\text{BU}}) + 0.5e(I_1)}{e(T_i)} \times 10^{-3} \text{ W},$$

$$T = \frac{E}{(\bar{P} + P_{\text{LK}}) \times (24 \times 365)} = \frac{E}{((1.8e(U_{\text{BU}}) + 9e(B_{\text{BU}}) + 0.5e(I_1))/e(T_i)) \times 10^{-3} + ((E \times 10\%)/(24 \times 365))} \times \frac{1}{8760} \quad (49)$$

$$= \frac{3.12}{8760 \times ((1.8e(U_{\text{BU}}) + 9e(B_{\text{BU}}) + 0.5e(I_1))/e(T_i)) \times 10^{-3} + 0.312} (a).$$

3. Experimental Analysis and Simulation

3.1. Protocol Procedure Flowchart. This article uses MATLAB R2014b as a tool for simulation experiments. It is assumed that the channel is in an ideal state without noise interference, and the idle slot length and the delay slot length are both $a = 0.1$. The slot length when the information packet is successfully sent is 1. The number of channels is $N = 4$. The timeslot length when information packets collide is b ($0 < b \leq 1$). The timeslot lengths of the handshake frames RTS and CTS are, respectively, $\tau_R = 0.01$ and $\tau_C = 0.01$. The timeslot length of the monitoring information segment is ignored. The flowchart of the adaptive two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms is shown in Figure 4.

3.2. Analysis of Simulation Results. Figures 5–8 show the changes in throughput, collision rate, idle rate, and loss rate of the three-way handshake mechanism with the arrival rate when the collision durations b are, respectively, 0.1, 0.4, 0.7, and 1. It can be determined that the change in collision duration b exerts little effect on the throughput of the system when the system is under low load. When the arrival rate G of the system is constant, as the collision duration decreases, the throughput and loss rate of the three-way handshake mechanism of the channel will gradually increase. The channel throughput and mechanism loss rate will gradually increase, and the collision rate will gradually decrease, but this will exert a minimal effect on the channel idle rate. When the system is under a high load, the channel throughput, collision

$$T = \frac{E}{\bar{P} + P_{\text{LK}}} = \frac{E}{24 \times 365 \times \bar{P} + E \times 10\%} (a). \quad (48)$$

Combining formulas (12), (23), (24), and (19) in Section 1.2, we can get, in a mobile ad hoc network system, the average power $\bar{P}(W)$ and lifetime $T(a)$ of system nodes under the adaptive two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms are

rate, idle rate, and loss rate of the three-way handshake mechanism will approach stable values, complete collision will not occur, and the throughput and idle rate will not decrease to 0. The performance of the system can be appropriately improved by adjusting the collision duration b , thus showing that this protocol can appropriately improve the performance of the system compared to the conventional P-CSMA protocol.

Figure 9 shows the changes in the average transmission delay (ATD) curve of the iCSMA with the arrival rate when the collision durations b are, respectively, 0.1, 0.4, 0.7, and 1. When the collision duration of the system is constant, as the arrival rate G of the system increases, the ATD will gradually increase. When the arrival rate G of the system is constant, as the collision duration decreases, the ATD will gradually decrease.

Figure 10 shows the throughput change curve of the total system and four priorities. It can be determined from the figure that the higher the priority service of the node, the higher the throughput obtained by the system. Furthermore, the lower the priority service of the node, the lower the throughput obtained by the system. In the case of light load, the throughput of the total system and the throughput of each priority increase rapidly with the increase of the arrival rate G of the information packet. When the arrival rate G increases to approximately 6, the total throughput of the system and the throughput of each priority reach their respective maximum values, and then, they slowly decrease with increasing arrival rate G . When the arrival rate G increases to approximately 60, the total system throughput and the throughput of each priority can always be maintained at a stable value and will not decrease, and both will occupy available system resources at a certain ratio. While ensuring high-priority business QoS, the system also takes certain fairness into account [30].

FIGURE 4: System simulation flowchart of iCSMA protocol.

FIGURE 5: Throughput curves with changing b value. FIGURE 6: Collision curves with changing b value.

FIGURE 7: Idle rate curves with changing b value. FIGURE 8: Loss rate curves with changing b value.

Figure 11 shows how the lifetime T curves of system nodes based on the conventional P-CSMA protocol, three-dimensional probability CSMA, and this protocol change

FIGURE 9: iCSMA ATD with changing b value.

FIGURE 10: Throughput curves of each priority.

along with the arrival rate G . It can be determined from Figure 11 that the theoretical value and the simulation value of the lifetime T of the system nodes based on the conventional P-CSMA protocol, the three-dimensional probability CSMA, and this protocol essentially match, which illustrates the correctness of the theoretical derivation. At the same time, the lifetime T of the system nodes under the conventional P-CSMA ($p = 0.5$) and three-dimensional

FIGURE 11: The lifetime curves of three protocols.

FIGURE 12: The throughput curves of four protocols.

probability CSMA protocols will decrease rapidly with the increase of the arrival rate G , while the lifetime T of the system nodes under this protocol will decrease significantly

more slowly. When the channel is under high load, the lifetime of the system node under the conventional P-CSMA protocol ($p = 0.5$) can only be maintained for approximately 0.02 years, and the lifetime of the system node under the three-dimensional probability CSMA protocol can only be maintained for approximately 0.04 years. However, the lifetime of the node under this protocol can still be maintained for approximately 0.1 years, thus demonstrating the superiority of this protocol.

As can be determined from Figure 12, the overall performance of this protocol is far superior to the other three CSMA protocols. With the increase of the arrival rate G of information packets, the throughput of the channel will gradually increase under the four CSMA protocols. When the arrival rate G reaches a certain value, the throughput of the channel will gradually decrease. When the channel is under high load, the channels under the remaining four protocols will completely collide, and no information packet will be sent successfully. Under this protocol, the throughput of the channel will remain unchanged and stable at approximately 0.5, thus indicating the superiority of this protocol.

4. Conclusion

In view of the low performance of the conventional P-CSMA protocol, based on the variability of collision duration and the characteristics of each CSMA protocol, this paper proposes an adaptive multichannel multipriority two-dimensional probability detection and 1-stick joint control strategy carrier sense multiple access with variable collision duration and three-way handshake mechanisms in mobile ad hoc networks. First, according to the traditional dual-slot feature, the three-slot clock feature is realized by adjusting the collision duration, thereby increasing the throughput of the system and reducing the collision rate of the system. Secondly, combining 1-persistence with the two-dimensional probability joint control function and the three-way handshake mechanism realizes the monitoring of the entire network system. Then, in order to meet the multiuser and multiservice types, the multichannel and multipriority mechanism is introduced, so that users can take priority in the channel to transmit information packets according to the priority. Next, this paper introduces an adaptive mechanism to reasonably set the transmission probability of the information packet in the next timeslot according to the arrival rate of the information packet. It can ensure the stability of the system. In particular, the performance of the system under high load conditions is improved to ensure that the channel does not completely collide under high load conditions. Finally, further analysis with the battery model shows that the protocol can effectively improve the lifetime of system nodes.

Data Availability

The program and data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest

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