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A multi-channel load awareness-based MAC protocol for flying ad hoc networks

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Abstract

Flying ad hoc network (FANET) is a promising and special mobile Ad hoc network, connecting large number of flying unmanned aerial vehicles (UAVs) on battlefield through wireless link. Designing a multi-priority traffic differentiated medium access control (MAC) protocol with low delay, large capacity, high flexibility, and strong scalability is a great challenge in the researches and applications of FANETs. In order to overcome the disadvantages in IEEE 802.11 distributed coordination function (DCF) and time division multiple access (TDMA) protocols, a novel multi-channel load awareness-based MAC protocol for FANETs is presented in this paper. The multi-priority queueing and service mechanism, and the multi-channel load-based backoff mechanism involved in the protocol are intensively described. We further model the multi-priority queueing and service mechanism by the multi-class queueing theory, and model the backoff mechanism using the Markov chain model. Simulation results show that the protocol can differentiate services for different priorities in FANETs according to real-time channel state, providing effective QoS guarantee for transmissions of various information, and the network bandwidth resource is efficiently utilized.

Keywords: Flying ad hoc network, Medium access control protocol, Multi-channel, Load awareness, Queueing, Backoff

1 Introduction

Recently, unmanned aerial vehicles (UAVs) with the characteristic of low-cost, strong robustness, various applications etc., have become a high-tech with rapid growth and attracted much attention in both military and civil fields. Especially, multi-UAV system, which has the advantages of good scalability, high invulnerability and high efficiency, etc., can play an important role in multiple military operations, such as battlefield reconnaissance, border patrolling, communication relay, precious strike, etc. A flexible, dynamic, distributed, and robust communication network for multi-UAV is the basis and premise for task coordination between UAVs. Flying ad hoc network (FANET) [1–3] is the core technology for constructing UAV communication network. Not relying on prebuilt communication infrastructures, it can transmit multiple kinds of information between UAVs, such as control instruction, situational awareness, and reconnaissance intelligence, etc., through aeronautical wireless channel, thus forming a multi-hop, self-organized, temporary, and distributed network. Several key technologies, such as dynamic topology control [4] and routing protocol [5–7], etc., are used in FANET to achieve the interconnection of multiple UAVs. It can not only extend the communication coverage, provide high-reliability and high-robustness communication links, but also improve the efficiency of task execution for UAVs.

FANET is a special form of mobile ad hoc network (MANET), which has the following characteristics: (1) high-speed movement of nodes, which is the most significant difference between FANET and MANET. The speed of UAVs can reach 30–460 km/h, which is much higher than all mobile units on the ground. The UAVs move with high speed, which lead to dramatic change in network topology, resulting in interruption of communication links and continuous updating of topology structure. It brings great challenge to the design of network communication protocol. (2) Large-scale sparse distribution. UAVs operate independently in three-dimensional space, with a wide range of distribution, and its single hop communication distance can reach hundreds of kilometers. (3) Significant temporariness. FANET is generally used for emergent and specific tasks. In the process of different tasks, the type and number of UAVs are generally different. Furthermore, UAV often temporarily adjusts and changes its mission while performing tasks, so it needs to re-plan its path. (4) Coexistence of multiple communication services. UAV usually needs to transmit many types of service when it performs multi-functional tasks, and different types of service have different QoS requirements, such as delay, transmission rate, throughput, etc. For example, the opportunity to strike the target may lose while executing the strike task. Therefore, the command and control instructions sent by UAV must meet the requirements of high-speed transmission and low delay. While in battlefield situation awareness and cooperative reconnaissance tasks, the service transmitted by UAV, such as image, voice, and video, needs to have large throughput.

Medium access control (MAC) protocol, as one of the key technologies in FANET, mainly solves the allocation of wireless channel resources between multi-UAVs [8, 9]. It can influence the reliability and effectiveness of information transmissions and system throughput directly. Currently, the most widely used existing MAC protocols in FANET are IEEE 802.11 distributed coordination function (DCF) protocol [10–14], and time division multiple access (TDMA) protocol [15–19]. The IEEE 802.11 DCF adopts RTS/CTS frames to reserve channel resources in order to avoid collisions. However, the RTS/CTS handshaking mechanism is not suitable for the transmission of delay-sensitive service, due to the large transmission delay of interactive information in long communication range. As a fixed allocation MAC protocol, TDMA has the advantages of high throughput and large capacity. However, it needs to pre-assign time-slots for each node, and the transmission delay is seriously influenced by the number of nodes. Therefore, it is also not suitable for the large-scale, temporary, and highly dynamic FANET used in networked cooperative operations.

In order to implement tasks efficiently in different applications for multi-UAV system, the MAC protocol used in FANET should meet the following capacity requirements: (1) it can contain large number of nodes, usually hundreds of nodes; (2) it has distributed, centerless and dynamic access capability, and good expansibility; (3) it has high information transmission rate for a large amount of services, such as images, voices, and videos; (4) it can achieve high reliability and low latency of information transmissions, especially for important types of services in network; (5) it can meet the QoS requirement of multiple services and differentiate multiple traffic types with limited network resource.

In order to guarantee the co-transmissions of multiple services and meet the strict QoS requirement of time-sensitive information transmissions in FANETs, and overcome the problems of existing protocols, we are motivated to propose a novel multichannel load awareness (MCLA)-based MAC protocol in this paper. Based on real-time channel occupancy awareness, the protocol can differentiate multiple priority traffic, providing effective QoS guarantee for information transmissions, and the bandwidth resources are fully utilized. The protocol employs a simple and effective multi-priority queueing and service mechanism for multiple services. It also introduces a multichannel load-based backoff strategy to control the access of packets rationally and efficiently for multiple services.

Generally speaking, the major contribution of our work is that a novel random competitive MAC protocol for FANET is proposed. It has the following attractive advantages:

(1) It can support multiple service classes;

(2) It can guarantee extremely low delay and extremely high transmission rate for the highest priority service by admission control of other priority services;

(3) It involves a novel adaptive backoff algorithm, whose contention window depends on the priority of traffic and the number of active nodes in the network;

(4) It also involves a novel multi-priority queueing and service mechanism for multiple service classes;

(5) It controls the access of packets (except the highest priority service) to channel according to the busy-idle degree of channel.

The remainder of the paper is organized as follows. Section 2 briefly describes the review of some related work in this field. Section 3 presents the MCLA MAC protocol for FANE Ts, describes the components of the protocol in detail, and models it theoretically. In Section 4, simulations are performed to show the protocol performance and mathematical derivations are verified. We conclude our work in Section 5. Finally, Section 6 describes the design of the study, the setting, the type of participants or materials involved, a clear description of all interventions and comparisons, and the type of analysis used.

2 Related work

In recent years, some studies on MAC protocol for FANET have already been launched. The existing research achievements can be classified to the following four categories:

(1) The time slot assignment protocol represented by TDMA and its modified protocols [10–12]. This type provides QoS guarantees by means of the slot allocation algorithm and has the feature of large throughput. However, the slot allocation algorithm is usually complex, and it is just suitable for aeronautical communication system without strict timeliness requirement. Tunc et al. in [13] analyzed the performance of TDMA MAC protocol in airborne telemetry networks. Li et al. in [14] described an interference-based distributed TDMA algorithm (IDTA). Xie et al. in [15] proposed a space division multiple access (SDMA) protocol to support dual priority levels of services in aeronautical communications. The protocol used orthogonal beamforming over the antenna array to improve spectrum efficiency. Guo et al. in [16] proposed a TDMA-based token cycle scheduling scheme, in which the token slot is cycled in all active nodes. Li et al. in [17] presented a token circulation scheme-based code division multiple access (CDMA) protocol. In the scheme, a token continuously circulates around the network. It is able to take advantage

of multiuser detection functionality and allows for simultaneous transmissions from multiple transmitters to the same receiver.

(2) The time slot reservation protocol, represented by IEEE 802.11 DCF and its modified protocols, which is particularly suitable for distributed networks [18–20]. However, the carrier sensing multiple access (CSMA)-based MAC protocol is inherently inappropriate for providing QoS in highly dynamic FANET environment. The potentially long propagation delay of FANETs (roughly 2 ms for a 300 nautical mile air-to-air link) makes carrier sensing inadequate. Furthermore, the RTS/CTS mechanism in CSMA causes long time delay for packets.

(3) The random access protocol represented by ALOHA and its modified protocols. This type does not need slot assignment or reservation, thus latency can be reduced significantly. Wang et al. in [21] proposed an ALOHA-based MAC protocol, integrating Turbo coding, burst technology, asynchronous frequency hopping, and priority differentiation for airborne networks. It realized differential service for the high- and low-priority packets. However, it can only differentiate two priority services. This type of protocol can achieve low delay and good scalability in the light-loaded network, yet packet collision probability is increasing exponentially with the increase of network load, leading to degraded performance. Ripplinger et al. in [22] compared the network performance of TDMA versus ALOHA via modeling and simulating in frequency hopped airborne networks. Results show that the maximum throughput of TDMA is a little higher and the delay of TDMA is larger than that of ALOHA.

(4) The hybrid protocol. It combines the above two or three kinds of protocols. Li et al. in [23] proposed a two-layer hybrid multi-beam smart antennas-based MAC for hierarchical airborne mesh networks. For aircraft-to-aircraft (A2A) links, they use a scheduled, TDMA-like multi-beam oriented MAC scheme to achieve high throughput transmissions. For UAV-to-UAV (U2U) links, they use the conventional CSMA/CA scheme with omnidirectional antennas. In addition, for aircraft-to-UAV (A2U) links, they use a compressive sensing-based data polling scheme. This type of protocol is too complex to realize.

Therefore, as discussed above, the time slot assignment and reservation protocols cannot meet the QoS requirement of the highest priority service in both light load and heavy load conditions for FANETs. However, the random access protocol can provide a good scalability for the network and guarantee extremely low transmission latency for the highest priority service in light load conditions. In addition, some mechanisms can be introduced to improve the performance of this type of protocols under heavy load conditions. In our previous work, a priority differentiated and multi-channel (PDM) MAC protocol is proposed in [24] and a channel occupancy statistical prediction mechanism for the MAC protocol is proposed in [25]. In PDM protocol, the access of different priority packets to channel is controlled by an adaptive jitter mechanism, which provides differentiated QoS services for different priorities. Combined with auto regressive (AR) forecasting, the channel occupancy statistical prediction mechanism can accurately predict channel load for the MAC protocol based on channel load awareness.

3 Protocol description

3.1 General description of MCLA protocol

The MCLA protocol proposed in this paper is a distributed random contention MAC protocol. It includes five components, namely, the multi-priority queueing and service mechanism, packet admission control mechanism, channel occupancy statistical prediction mechanism, backoff mechanism, and multi-channel allocation mechanism, as shown in Fig. 1. The channel occupancy statistical prediction mechanism can determine channel busy-idle degree by statistical history information of channel load [25]. Each node senses channel load continuously by its receiver to obtain predicted value. Thereby, the predicted value is used for packet admission control mechanism and backoff mechanism. The packet admission control mechanism controls the access of packets to channels according to preset threshold of each priority and predicted channel occupancy state. The multi-channel dynamic allocation mechanism is used to allocate channel resource to different services rationally. In this paper, we mainly study the multi-priority queueing and service mechanism and the backoff mechanism in the protocol.

The fundamental principle of MCLA protocol is described as follows:

(1) Each node in the network has a sending buffer of the same size. When information is generated, it is split into multiple packets of the same length to be transmitted in node buffer. Packets of the same priority line up in a separate queue.

(2) Total channel resource is divided into *C* paralleled channels, and interference between different channels is ignored.

(3) Each node has a sending access and *C* receiving accesses. The system works on half-duplex mode.

(4) The status of each node in the network is equal, and each node can generate traffic of *P* priority classes. All packets have the same length and transmission rate. Furthermore, the service of the highest priority has a very strict QoS requirement in timeliness and reliability.

(5) Generally, the admission of packets to channels is determined by the channel threshold of the packet priority and current channel busy-idle degree. For the timeliness of transmission of the highest priority packets, the admission of these packets is not controlled by channel threshold. That is to say, the channel threshold is not set for the highest-priority packets. However, different channel thresholds are set for each priority service respectively (except the highest priority). The admission of packets is controlled by comparison between the channel threshold of their priority and the current channel busy-idle degree. If the current channel busy-idle degree is lower than the channel threshold, the packet can have access to channel immediately. Otherwise, it cannot be transmitted immediately and will go through the backoff stage. After the backoff stage, whether it can have access to channel will be judged once again.

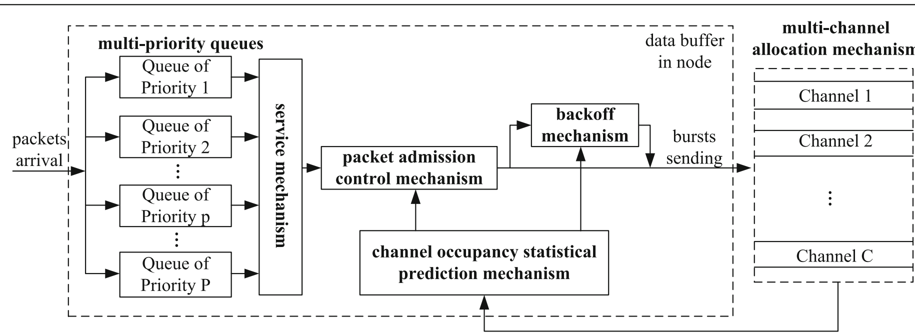

Fig. 1 Components of the MCLA protocol

(6) The MCLA protocol adopts the random access mechanism. Each node chooses a channel randomly to send packets with a probability $1/C$ and can receive packets in all channels. If only one packet is transmitted in a channel during a slot time, it can be transmitted successfully. However, if several packets are transmitted in a channel simultaneously, a collision will happen. The channel transmission delay of a burst is μ, and if the transmission interval between the two bursts sent in the same channel is less than μ, a collision will happen. For example, a collision will happen in channel c, as shown in Fig. 2. At that time in the receiver, if the receiving power of a packet is larger than or equal to ρ times of the sum of receiving power of other packets, the packet can still be received successfully.

(7) When a collision happens, the node whose packet is transmitted unsuccessfully will wait for W_{bf} slot times according to the backoff scheme and send the packet once again. The value of W_{bf} is determined by current number of active nodes in the network. The detailed description is given in Section 3.3.

(8) The transmission time of a packet in a single hop is a slot time.

The process of node state transition in MCLA protocol is shown in Fig. 3. Each node in the network works based on the following state transition scheme. (1) In the state "initialization/idle", if node receives packets from the upper layer, the packets are inserted into the corresponding priority queue. (2) After the new arrival packets are inserted into the queue, compare the busy-idle degree of channel at present with the channel threshold preset for each priority according to the admission control mechanism, and then decide whether enter into the state "send the head packet of the queue" or enter into the state "backoff". (3) In the state "backoff", when new packets arrive, if the corresponding priority queue is not full, insert the packets into the queue, otherwise discard the packets. When there exist corresponding idle channels, enter into the state "send the head packet of the queue". (4) In the state "send the head packet of the queue," when new packets arrive, if the corresponding priority queue is not full, insert the packets into the queue, otherwise discard the packets. (5) After the state "transmission completed," according to whether all queues are empty and the busy-idle degree of channel, the state of the node can enter into "send the head packet of the queue," or "initialization/idle," or "backoff."

For the above process in MCLA protocol, let us further describe the state transition of the highest priority packet and other priority packet, respectively. For the highest priority packet, it will be inserted into the highest priority queue when it arrives. After the packets arrived earlier in the highest priority queue are transmitted, it will enter into the state "send the head packet of the queue." When it is transmitted successfully, it will enter into the state "transmission completed." For the other priority packet, it may experience more complex state transitions. When it arrives, it will be inserted into its corresponding priority queue. When it reaches the head of its priority queue and the higher priority queues are empty, it acquires the chance to have access to channel.

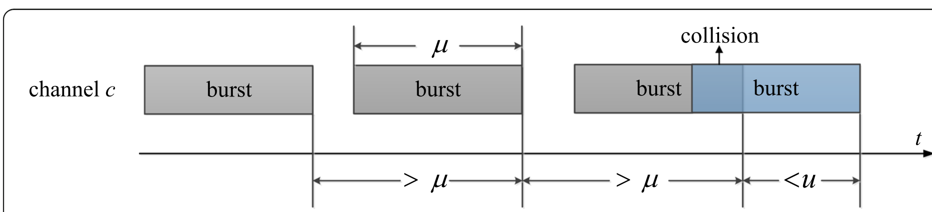

Fig. 2 Collision of bursts in channel c

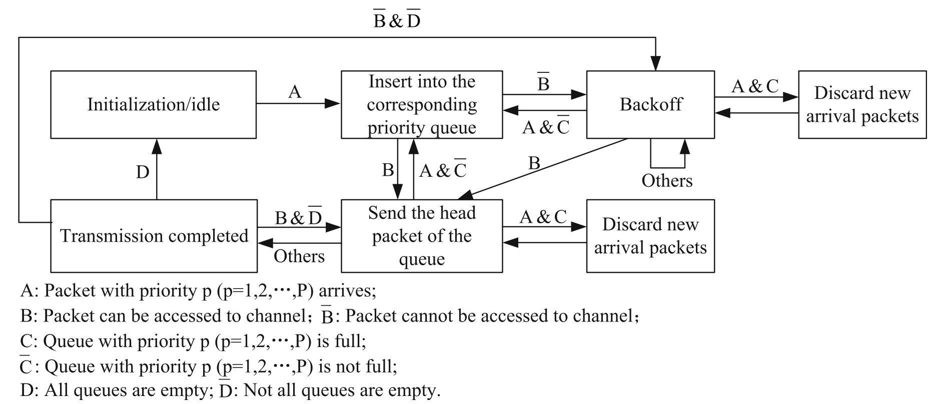

Fig. 3 Node state transition in MCLA protocol

Whether it can have access to channel is be determined by the busy-idle degree of channel at present and the channel threshold preset for its priority. If the current busy-idle degree of channel satisfies the access to channel, it will enter into the state "send the head packet of the queue." Otherwise, it will enter into the state "backoff." If it enters into the state "send the head packet of the queue" and the packet is transmitted successfully, it will enter into the state "transmission completed." If it enters into the state "backoff" and when the backoff period ends, it has another chance to have access to channel. Whether it can have access to channel should still be judged by the current busy-idle degree of channel.

3.2 Multi-priority queueing and service mechanism

The traffic in the network has P priority classes, where the priority 1 service is the highest priority, the priority 2 service is the sub-highest priority, and the priority P service is the lowest priority. Supposing that the sending buffer in node is large enough, the queue overflow is not considered in this paper. Furthermore, it is supposed that the arrival of packets for each priority is considered as a Poisson process, the service provided for packets by server obeys general distribution, and there is only 1 server in the system. Therefore, the packet queue in each node buffer is a multi-priority M/G/1 queueing system, as shown in Fig. 4. Let the packet arrival rate from the highest priority to the lowest priority be λ_1, λ_2, $\cdots$, $\lambda_{P,}$ respectively, the mean service time is $\frac{1}{\mu_1}, \frac{1}{\mu_2}, \cdots, \frac{1}{\mu_P}$ respectively, and the second moment of service time is $\overline{X_1^2}, \overline{X_2^2}, \cdots, \overline{X_P^2}$ respectively. Let N_Q^p, W_p and ρ_p denote the waiting queue length, waiting time, and utilization ratio of the priority p packets, respectively.

The system is a single-server and multi-queue system, and serves packets from high priority to low priority. Supposing that the traffic of the highest priority is extremely low, the preemptive-resume service strategy is employed for it. That is to say when the highest priority packet arrives, the transmission of other priority packet will be interrupted, and the new arrived packet will be served preferentially. When the service is over, the interrupted packet will be transmitted from the breakpoint. Furthermore, the backoff scheme is not used for the highest priority traffic. For the priority $2 \le p \le P$ packets, the system adopts the non-preemptive strategy, i.e., if a higher priority packet

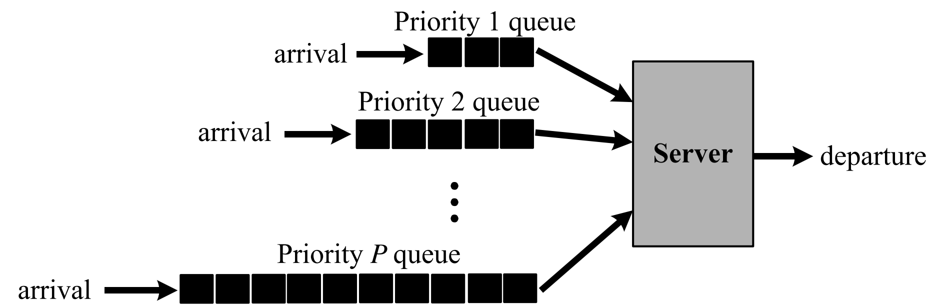

Fig. 4 Multi-queue single-server queueing system in each node buffer

arrives, it will be served when the service for the current lower priority packet finishes. In addition, before serving, the system should decide whether the packet can be served immediately according to the current channel busy-idle degree. If it satisfies the service condition, the packet will be accessed immediately; otherwise, it will wait for several slot times according to the backoff scheme. After the backoff phase, it will be judged again whether it can be served or enter into another backoff phase. The duration of each backoff phase is denoted as V_1, V_2, $\cdots$, which are independent identically distributed random variables and are independent of the packet priority. The mean value of V_1, V_2, $\cdots$ is $\overline{V}$. Except for the priority 1 packets, all packets will experience $m(m = 0, 1, 2, \cdots)$ backoff periods.

In the following, the expected delay T_p will be derived. T_p is comprised of two parts: ① the expected service time $1/\mu_p$ of packets, ② the expected waiting time of packets. The expected waiting time W_p of the priority p packet contains two parts: ① the service time W_{old}^p of the priority 1 to p packets which have already existed in the system when the priority p packet arrives; ② the service time W_{new}^p of priority 1 to $p-1$ packets which arrives while the priority p packet is waiting for service. Thus,

$$T_p = \frac{1}{\mu_p} + W_p = \frac{1}{\mu_p} + W_{old}^p + W_{new}^p \tag{1}$$

Where W_{old}^p can be derived according to a single-priority M/G/1 queueing system with server's vacation. In the queueing system, only priority 1 to p packets need to be considered, while priority $p+1$ to P packets can be neglected. According to the M/G/1 queueing theory, we have

$$W_{old}^p = \frac{R_p}{1-\rho_1-\rho_2-\cdots-\rho_p} \tag{2}$$

Where R_p is the mean residual service time of packets, and ρ_p is the utilization ratio of the priority p packets. R_p will be derived as follows.

When a new packet arrives, it may encounter two situations: (1) there is a packet receiving service; (2) there is a packet in backoff stage.

Let $M_p(t)$ and $L(t)$ denotes the number of packets arrived and the number of backoff times during interval $[0, t]$ respectively. Thus, the mean residual service time R_p of the priority p packets can be expressed as

$$R_p = \frac{1}{t}\int_0^t r(\tau)d\tau = \frac{1}{t}\sum_{i=1}^{M_1(t)}\frac{1}{2}{X_{1i}}^2 + \frac{1}{t}\sum_{i=1}^{M_2(t)}\frac{1}{2}{X_{2i}}^2 + \cdots + \frac{1}{t}\sum_{i=1}^{M_{p-1}(t)}\frac{1}{2}{X_{(p-1)i}}^2 + \frac{1}{t}\sum_{i=1}^{L(t)}\frac{1}{2}{V_i}^2$$
$$= \frac{1}{2}\frac{M_1(t)}{t}\frac{\sum_{i=1}^{M_1(t)}{X_{1i}}^2}{M_1(t)} + \frac{1}{2}\frac{M_2(t)}{t}\frac{\sum_{i=1}^{M_2(t)}{X_{2i}}^2}{M_2(t)} + \cdots + \frac{1}{2}\frac{M_{p-1}(t)}{t}\frac{\sum_{i=1}^{M_{p-1}(t)}{X_{(p-1)i}}^2}{M_{p-1}(t)} + \frac{1}{2}\frac{L(t)}{t}\frac{\sum_{i=1}^{L(t)}{V_i}^2}{L(t)} \tag{3}$$

Where $\frac{M_1(t)}{t}$ is the arrival rate λ_1 of the priority 1 packets, $\frac{M_2(t)}{t}$ is the arrival rate λ_2 of the priority 2 packets, ..., $\frac{M_{p-1}(t)}{t}$ is the arrival rate λ_{p-1} of the priority $p-1$ packets, and $\frac{L(t)}{t}$ is the mean arrival rate of the backoff stages.

In unit time, the proportion of transmission of the priority p packets can be expressed as $\rho_p = \frac{\lambda_p}{\mu_p}$, and the proportion of backoff stage is $1 - \sum_{i=1}^{p-1}\rho_i$. Thereby, the mean arrival rate of the backoff stages is $\frac{1 - \sum_{i=1}^{p-1}\rho_i}{\overline{V}}$.

Let $t \to \infty$, and the mean residual service time is

$$R_p = \frac{1}{2}\lambda_1\overline{{X_1}^2} + \frac{1}{2}\lambda_2\overline{{X_2}^2} + \cdots + \frac{1}{2}\lambda_{p-1}\overline{{X_{p-1}}^2} + \frac{1}{2}\frac{1 - \sum_{i=1}^{p-1}\rho_i}{\overline{V}}\overline{V^2} = \frac{1}{2}\sum_{i=1}^{p-1}\lambda_i\overline{{X_i}^2} + \frac{1}{2}\frac{1 - \sum_{i=1}^{p-1}\rho_i}{\overline{V}}\overline{V^2} \tag{4}$$

As W_{new}^p is the service time of the newly arrived priority 1 to $p-1$ packets since the priority p packet arrives, we have

$$W_{new}^p = \frac{\lambda_1}{\mu_1}T_p = \rho_1 T_p, \quad p > 1 \tag{5}$$

Thus, the expected delay T_p can be derived from (1), (2), (4), and (5).

3.3 Multi-channel load-based backoff mechanism

In FANETs, the node which has packets to send is defined as an active node. In the backoff mechanism, the size of contention window is determined by the number of active nodes in the meantime. The arrival of packets of all priorities is a Poisson process with the arrival rate $\sum_{p=1}^{P}\lambda_p$. In MCLA protocol, each packet is divided into multiple bursts to be transmitted in channel. The duty cycle of burst in a packet is R, which means the ratio of the transmission time of a burst in channel to that of the original packet in the channel. The node number in the network is N. According to the Poisson theory, the number of active nodes in the network is

$$n = N\left(1 - e^{-\frac{2\sum_{p=1}^{P}\lambda_p}{RC}}\right) \tag{6}$$

According to the principle of MCLA protocol, the expression of contention window can be constructed as

$$W_{bf} = \left\lceil -\frac{2}{\ln \frac{n}{N+1}} \right\rceil \tag{7}$$

In backoff stage i, the backoff duration is a random value, thus can be denoted as

$$W_i = Random\left[1,\ \min\left(W_{bf}, W_{\max}\right)\right] \tag{8}$$

where $W_{\max}$ is the maximum value of contention window we defined. When a node experiences multiple consecutive backoff stages, the size of contention window increases linearly until it reaches $W_{\max}$.

3.4 Modeling of the backoff mechanism

In the following, the two-dimensional Markov chain is adopted to model the backoff mechanism. Let $b_{i,j} = \lim_{t\to\infty} P\{u(t) = i, v(t) = j\}$ denote the steady-state probability of every state in Markov chain, where i is the backoff stage and j is the size of the contention window. The backoff state space of node can be expressed as $\Omega = \{(i,j) | i \in \{-1, 0, 1, 2, \cdots, m\}, j \in \{0, 1, \cdots, W_i - 1\}\}$, where the state $(-1, 0)$ denotes the state after a burst is transmitted successfully, or a burst cannot still have access to channel through the maximum backoff times. The state transition in the model is shown in Fig. 5. The one-step state transition probability is

$$\begin{aligned} &P\{i+1, j+1|i, j\} = \\ &P\{u(t+1) = i+1, v(t+1) = j+1|u(t) = i, v(t) = j\} \end{aligned} \tag{9}$$

From Fig. 5, we can acquire the state transition probability

$$\begin{cases} P\{-1, 0|m, 0\} = 1 \\ P\{-1, 0|i, 0\} = 1 - p_{col}, i\in[0, m-1] \\ P\{\mathrm{i}, j|i, j+1\} = 1, i\in[0, m], j\in[0, W_i - 1] \\ P\{i, j|i-1, 0\} = p_{col}/W_i, i\in[1, m], j\in[0, W_i - 1] \\ P\{m, j|m, 0\} = p_{col}/W_m,\ \ j\in[0, W_m - 1] \\ P\{0, j|-1, 0\} = q/W_0,\ \ j\in[0, W_m - 1] \end{cases} \tag{10}$$

where p_{col} is the collision probability of bursts, which is equal to the probability that at least one node in $n-1$ active nodes send bursts to the same channel at the same time slot. It can be expressed as

$$p_{col} = \frac{1 - (1 - p_{in})^{n-1}}{C} \tag{11}$$

where p_{in} is the probability that a burst can be accessed to the channel after the current backoff stage. From Fig. 5, it can be expressed as

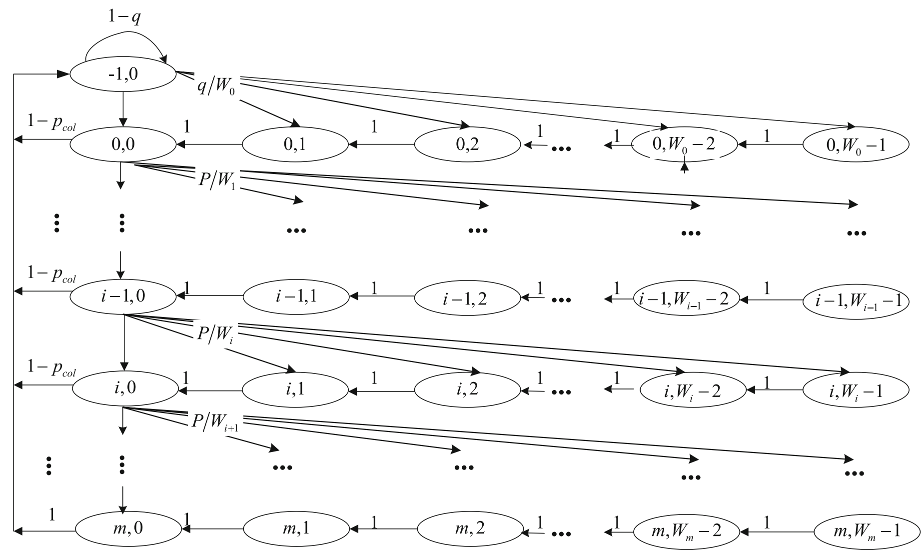

Fig. 5 2-dimensional Markov chain model for the proposed backoff mechanism

$$p_{in} = \sum_{i=0}^{m} b_{i,0} = \frac{(1 - p_{col})b_{0,0}}{1 - (p_{col})^m} \tag{12}$$

In (10), q is defined as the probability that there are packets arrived during the time slot T_σ. Therefore, we can obtain

$$q = 1 - e^{-\lambda T_\sigma} \tag{13}$$

According to (10) and Fig. 5, we have

$$\begin{cases} b_{0,j} = \dfrac{W_0 - j}{W_0} \cdot q, j\in[1, W_0 - 1] \\ b_{i,j} = b_{i-1,0} \cdot \dfrac{W_i - j}{W_i} \cdot (p_{col})^i, i\in[1, m], j\in[1, W_i - 1] \end{cases} \tag{14}$$

The expressions of $b_{i,j}$ and $b_{-1,0}$ with $b_{0,0}$ can be obtained from (14)

$$b_{i,j} = \frac{W_i - j}{W_i} (p_{col})^i b_{0,0}, i\in[0, m], j\in[0, W_i - 1] \tag{15}$$

$$b_{-1,0} = b_{0,0}/q \tag{16}$$

According to the definition of Markov chain, all states in Fig. 5 should meet the requirement of normalization, namely

$$b_{-1,0} + \sum_{i=0}^{m} \sum_{j=0}^{W_i - 1} \frac{W_i - j}{W_i} \cdot (p_{col})^i b_{0,0} = 1 \tag{17}$$

According to (11) to (15), we have

$$b_{0,0}=\frac{1}{\frac{1}{q}+\sum_{i=0}^{m}\sum_{j=0}^{W_i-1}\frac{W_i-j}{W_i}\cdot(p_{col})^i} \tag{18}$$

3.5 Metrics for protocol performance

3.5.1 Mean MAC delay of the backoff mechanism

Let $E[T_{MAC}]$ denote the mean MAC delay, which is the average time from the beginning of backoff stage to the time that the burst is accessed to channel or abandoned. It can be easily obtained that

$$E[T_{MAC}]=\frac{\sum_{i=0}^{m}(1-p_{col})^i W_i T_\sigma}{2m} \tag{19}$$

3.5.2 Mean end-to-end delay

The mean end-to-end delay $E[T]$ is the sum of the waiting time, the backoff time and the propagation time. T_p derived in part C of Section III is the sum of the waiting time and the backoff time. Define $E[T_{pro}]$ as the packet propagation delay, and its value is related to the communication distance. Let d_{com} be the mean communication distance in a single hop, and c is the speed of light. So $E[T_{pro}]$ can be calculated as

$$E\left[T_{pro}\right]=\frac{d_{com}}{c} \tag{20}$$

Therefore, $E[T]$ can be expressed as

$$E[T]=E\left[T_p\right]+E\left[T_{pro}\right] \tag{21}$$

(3) Network throughput

Here, S is defined as network throughput, meaning the overall bursts accessed to channel within the unit time. It can be expressed as

$$S=L(1-p_{col})\sum_{i=0}^{m}b_{i,0}\sum_{p=1}^{P}\lambda_p=\frac{L(1-p_{col})^2 b_{0,0}\sum_{p=1}^{P}\lambda_p}{1-(p_{col})^m} \tag{22}$$

where L is the burst length.

4 Simulation

In this section, the performance of MCLA protocol is verified through simulations in OMNeT++. Firstly, the theoretical model of the backoff mechanism is verified. Then, its performance is compared with some traditional backoff mechanisms by simulations, such as binary exponential backoff (BEB), multiple increase linear decrease (MILD) mechanisms. The simulations are based on the following assumptions:

(1) All nodes are randomly distributed among the scenario in the beginning and make uniform linear motions with the speed of 1~100 m/s and random directions in simulations. A fully connected MANET is formed by all nodes.

(2) Every node has a sending pathway and several receiving pathways as many as the channels. The receiving pathways are not blocked when packets are sending.

(3) The arrival of packets obeys the Poisson distribution, and all packets are of the same length and data transmission rate.

(4) When packets have access to channels, the channel is chosen randomly among all the available channels.

The detailed simulation parameters are shown in Table 1.

Theoretical and simulation results of the mean MAC delay and throughput in MCLA protocol are shown in Fig. 6 and Fig. 7. We can see that the theoretical results are in accordance with the simulation results, which indicate the accuracy of the theoretical model in Section III. As depicted in Fig. 6, the mean MAC delay of each priority service is different, because the authorities of packets of different priorities accessed to channels are different under the same channel occupancy rate. Hence, service differentiation is achieved in MCLA protocol. In addition, with the increase of packet arrival rate, the mean MAC delay of the highest priority packet keeps stable, and that of the other priorities increases continuously. It indicates that MCLA protocol can guarantee the transmission of the highest priority service with extremely low delay. As depicted in Fig. 7, the system throughput of MCLA protocol can reach to 8 Mbit/s and keep stable due to the mechanisms adopted, and it can meet the requirements of mass data transmitted in FANETs.

The performance of the backoff mechanism in MCLA protocol is compared with that of another two traditional backoff mechanisms, BEB and MILD mechanism in Fig. 8 and Fig. 9. From Fig. 8, we can learn that the mean MAC delay increases with the increase of the packet arrival rate. Compared with BEB and MILD mechanism, the mean MAC delay of different priorities of the backoff mechanism in MCLA protocol is notably lower. From Fig. 9, it can be acquired that with the increase of the packet arrival rate, the network throughput of different backoff mechanisms all tends to reach a saturation value. The network throughput of the backoff mechanism in MCLA protocol is higher than that of MILD and BEB mechanism. It indicates that MCLA protocol is more suitable to guarantee transmission of mass data in FANETs. The reason why the performance of the backoff mechanism in MCLA protocol is better than that of BEB and MILD mechanism is that the proposed backoff mechanism adopts the adaptive adjustment of contention window, which can change the length of contention window according to the current traffic loads in FANET.

The mean end-to-end delay of the MCLA protocol is compared with that of TDMA and IEEE 802.11 DCF in Fig. 10. From Fig. 10, we can acquire that the end-to-end delay in MCLA protocol is lower than that of TDMA and 802.11 DCF. The reason is that MCLA protocol adopts the multi-priority queueing and service mechanism and the adaptive backoff mechanism. These mechanisms reduce the end-to-end delay of packets effectively.

From the above simulation, we can conclude that (1) when the network is in light load, the performance difference between different mechanisms is minor; (2) in heavy load, the performance of MCLA protocol is much better than that of some traditional protocols, such as TDMA and IEEE 802.11 DCF protocol; (3) MCLA protocol can differentiate multiple services and guarantee the extremely low delay of the highest priority service.

5 Results and discussion

The paper presents a novel multi-channel load awareness-based and distributed random contention MAC protocol for FANETs. This protocol mainly consists of five parts,

Table 1 Parameters of theoretical analysis and simulation

Parameter	Value	Parameter	Value
Number of nodes N	50	Scenario size	6×6 km^2
Number of channels C	10	Duty cycle of burst R	0.125
Packet length	600 bits	Length of time slot T_σ	50 μs
Data transmission rate	2 Mbit/s	Node communication range	1 km
Node speed	1~20 m/s	Communication frequency	2.4 GHz
Maximum value $W_{\max}$ of contention window	$16T_\sigma$	Number of priorities of packets P	4
Proportion of packet arrival rate of different priorities	$\lambda_1:\lambda_2:\lambda_3:\lambda_4=1:5:8:15$		

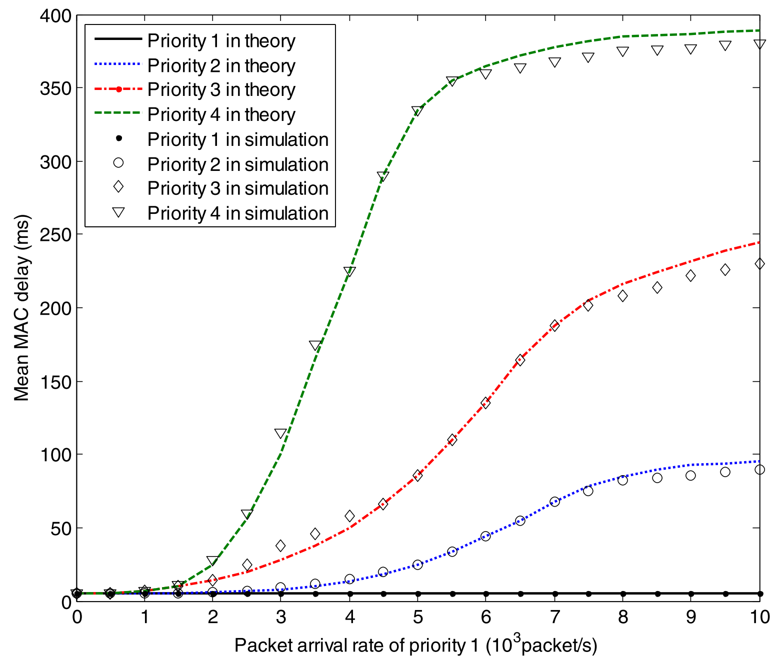

Fig. 6 Mean MAC delay of different prority service in MCLA protocol

i.e., multi-priority queueing and service mechanism, packet admission control mechanism, channel occupancy statistics and predicting mechanism, backoff mechanism, and multi-channel allocation mechanism. We further depict the queueing mechanism and the backoff mechanism, and model the mechanism using the Markov chain model. Simulation results show that the protocol has much better performance under heavy

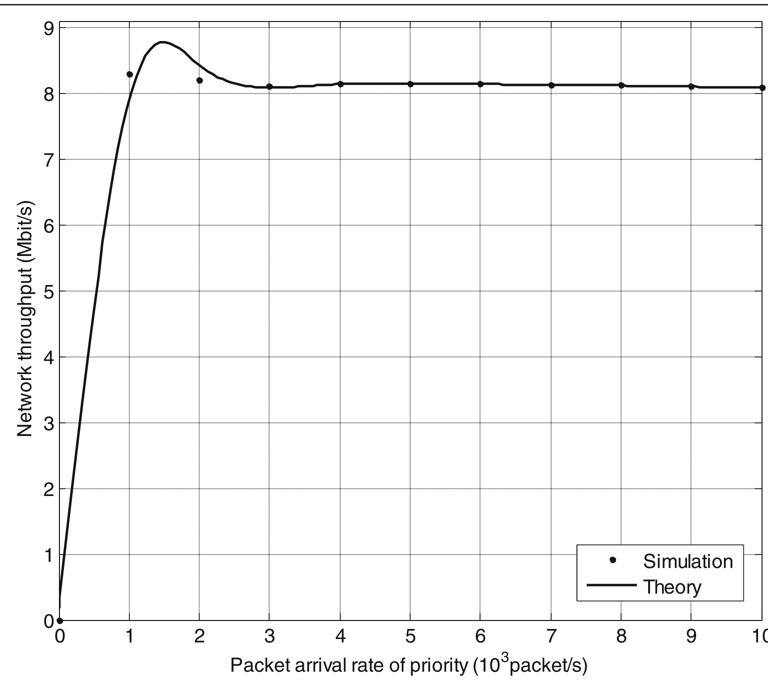

Fig. 7 Network throughput of the backoff mechanism in MCLA protocol

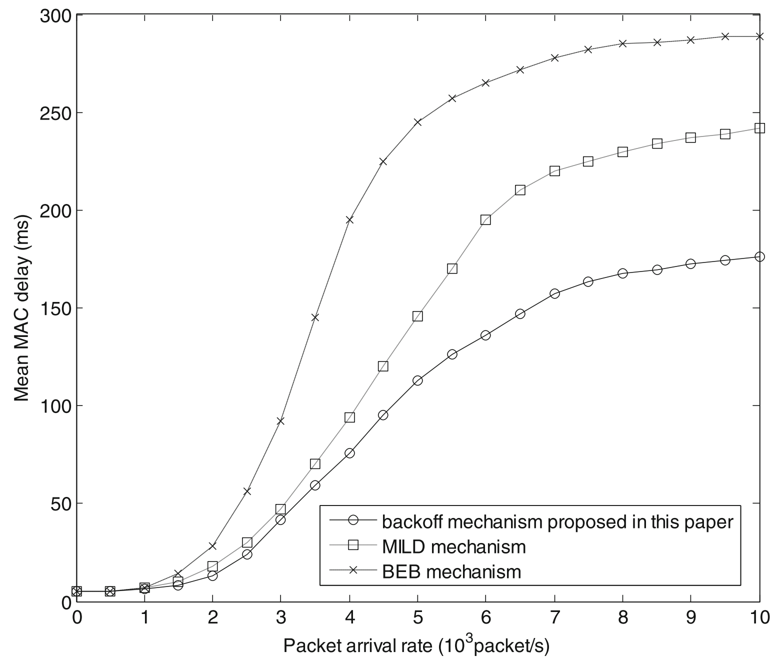

Fig. 8 Mean MAC delay in different backoff mechanisms with different packet arrival rates

load than several traditional MAC protocols, because it controls the access of packets to channel according to real-time channel state and adjusts the backoff duration according to the number of active nodes in the network.

In the future, we will further improve and optimize the protocol, ensuring the QoS requirement of different priority services.

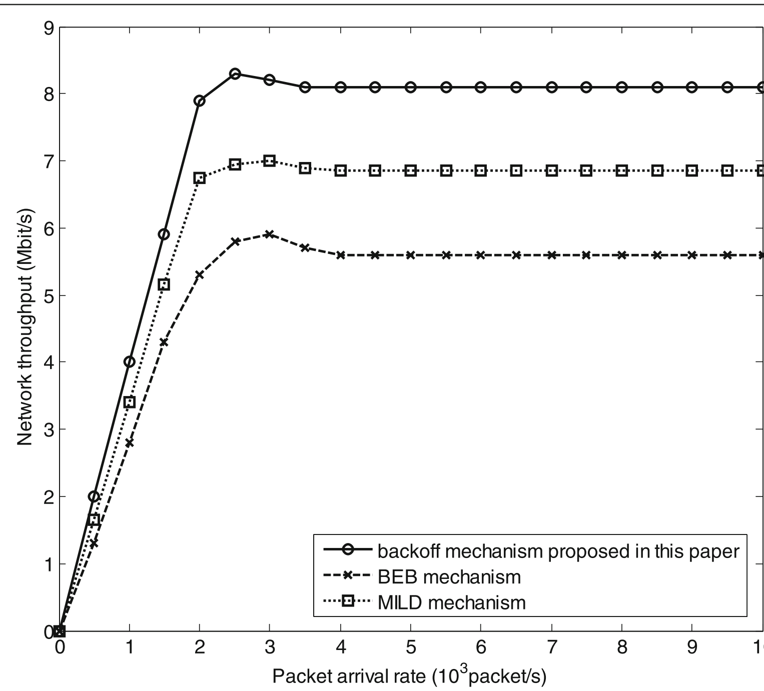

Fig. 9 Network throughput in different backoff mechanisms with different packet arrival rates

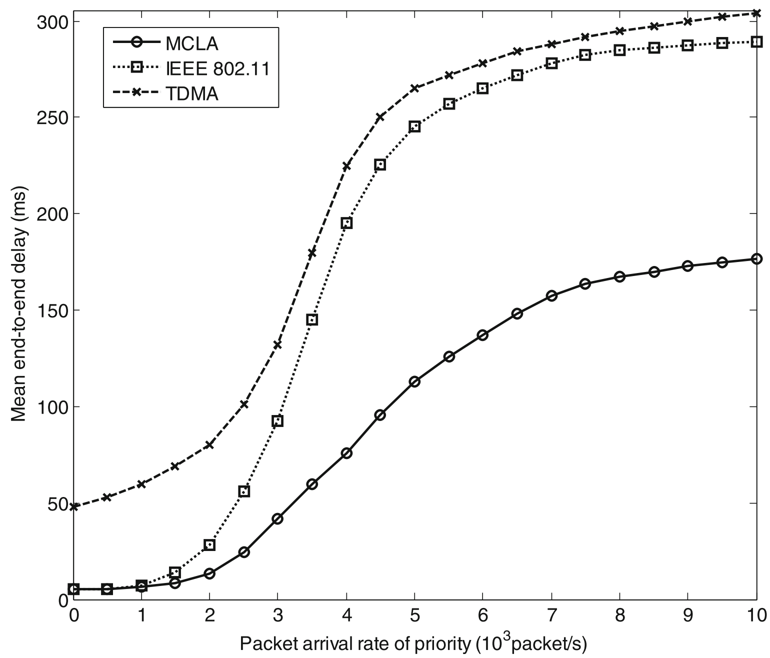

Fig. 10 Mean end-to-end delay of packets in different MAC protocols

6 Methods/experimental

In order to overcome the disadvantages in IEEE 802.11 DCF and TDMA protocol, a novel multi-channel load awareness-based MAC protocol for FANETs is proposed in the paper. The main components and functions of the protocol are briefly described, and the multi-priority queueing and service mechanism is modeled using multi-priority queueing theory while the adaptive backoff algorithm is modeled using two-dimensional Markov chain model. Finally, simulations are conducted in OMNeT++ to verify the correctness of the mathematical derivations and the performance of the proposed protocol. According to the performance comparison of BEB, MILD, and the proposed protocol, the performance superiority of the MCLA protocol is shown.

Abbreviations

FANET: Flying ad hoc network; UAV: Unmanned aerial vehicles; MAC: Medium access control; DCF: Distributed coordination function; TDMA: Time division multiple access; QoS: Quality of service; MCLA: Multi-channel load awareness; CDMA: Code division multiple access; IDTA: Interference-based distributed TDMA algorithm; CSMA: Carrier sensing multiple access; A2A: Aircraft-to-aircraft; U2U: UAV-to-UAV; A2U: Aircraft-to-UAV; PDM: Priority differentiated and multi-channel; AR: Auto regressive; MILD: Multiple increase linear decrease; BEB: Binary exponential backoff

Consent to participate

not applicable

Authors' contributions

BZ proposed the main idea and is the main writer of this paper. YL, WC, HW, and WL assisted in the simulations and analysis. All authors read and approved the final manuscript.

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Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Ethics approval and consent to participate

The study was approved by the Ethics Review Committee (ERC) of the Deputy of Research at Kermanshah University of Medical Sciences (IR.KUMS.REC.1399.000).

Competing interests
The authors declare that they have no competing interests.

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