

Article

MA-SPMA: A Multi-Hop Adaptive MAC Protocol for Flying Ad Hoc Networks Based on Two-Dimensional Queueing and Dual-Round Decision

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Abstract

Aiming at the problems of the traditional Statistical Priority-Based Multiple Access (SPMA) protocol in multi-hop Flying Ad Hoc Networks (FANETs), such as single-dimensional queueing only according to priority, unreasonable First-In-First-Out (FIFO) scheduling, high timeout dropping probability of multi-hop forwarding packets, and insufficient utilization of channel opportunities, this paper proposes a multi-hop adaptive SPMA protocol (MA-SPMA) suitable for dynamic multi-hop scenarios. The protocol adopts the Neighbor-Priority Two-Dimensional Queueing (NPTQ) mechanism to store packets jointly according to the next-hop neighbor and priority. A Priority-Utility Dual-round Decision (PUDD) mechanism is designed: in the first round, candidate queues that meet channel load conditions are selected in parallel; in the second round, a utility function constructed by normalized delay, priority, and the end-to-end transmission success rate is used to select the optimal packet for transmission. Theoretical analysis shows that the time and space complexity of MA-SPMA are linearly related to the number of neighbor nodes, with controllable overhead, which is suitable for resource-constrained Unmanned Aerial Vehicle (UAV) platforms. In the MATLAB simulation environment, the Reference Point Group Mobility (RPGM) model is used to construct a multi-hop topology, and comparisons are conducted with two typical improved protocols for multi-hop networks: DCLS-SPMA and BiLSTM-SPMA. The results show that the proposed protocol can significantly improve the end-to-end transmission success rate and network throughput, with more obvious advantages in scenarios with a high proportion of multi-hop services. This paper provides an effective solution for Medium Access Control (MAC) protocol design in FANETs.

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1. Introduction

Flying Ad Hoc Networks (FANETs) are decentralized distributed wireless communication networks composed of Unmanned Aerial Vehicle (UAV) nodes without relying

on communication infrastructure [1,2]. In such networks, UAV nodes serve as data transmitters, receivers, and relays simultaneously. When the source node and the destination node are beyond the single-hop communication range, data packets can be forwarded to the destination node through intermediate nodes in a multi-hop manner. FANETs have the advantages of flexible networking, strong mobility, and good survivability [3]. They can support various services such as cluster control, real-time situation awareness, sensor data sharing, and cooperative task execution, showing broad application prospects in emergency communication, logistics transportation, agricultural monitoring, and other fields.

In FANETs, the Medium Access Control (MAC) protocol is responsible for node access control and wireless channel resource allocation. Under a decentralized architecture, how to realize distributed efficient access and optimal resource allocation through optimized MAC protocol design while meeting the Quality of Service (QoS) requirements of multiple services and improving overall network performance is a key problem to be solved urgently. Traditional MAC protocols are mainly divided into two categories: contention-based protocols and allocation-based protocols [4]. Contention-based protocols, represented by the ALOHA protocol [5] and CSMA protocol [6], can provide low delay when the network scale is small. However, as the number of nodes increases, the collision probability rises sharply, and performance indicators such as the transmission success rate, delay, and throughput degrade significantly. Allocation-based protocols, represented by the TDMA protocol [7,8], adopt a slot allocation method combining fixed allocation and dynamic request, which can effectively avoid slot competition among multiple nodes and maintain a high transmission success rate even in large-scale networks. Nevertheless, TDMA cannot support on-demand transmission, and the queueing delay increases with the number of nodes, making it difficult to meet the ultra-low delay requirements of high-priority services in UAV networks.

Statistical Priority-Based Multiple Access (SPMA) is a contention-based MAC protocol with traffic control [9]. The core idea of SPMA is to allow random transmission of all priority services when the channel load is light and restrict access of low-priority services when the channel load is heavy so as to reserve a clean channel environment for high-priority services and preferentially guarantee their QoS. In TTNT (Tactical Targeting Networking Technology) networks, SPMA ensures that the end-to-end delay of the highest-priority service is lower than 2 ms and the first transmission success rate is not lower than 99% [10].

The working mechanism of the SPMA protocol is shown in Figure 1. Packets arriving at the network layer are placed into different priority queues of the SPMA protocol layer according to the priority of different services. Each priority queue is configured with a pre-defined transmission threshold; the higher the priority, the larger the threshold. In each time slot, the SPMA protocol checks each priority queue sequentially from high priority to low priority for the transmission decision: if the current priority queue is not in the backoff process and there are packets waiting to be sent, the Channel Occupancy Statistics (COS) fed back by the physical layer is compared with the threshold of the priority queue. If the COS is smaller than the threshold, it means that the current channel load is light, and the head-of-line packet of the queue is handed over to the physical layer for transmission; otherwise, it means that the channel load is heavy, transmission is not allowed, the priority queue is set into backoff, and no lower-priority queues are checked until the next time slot.

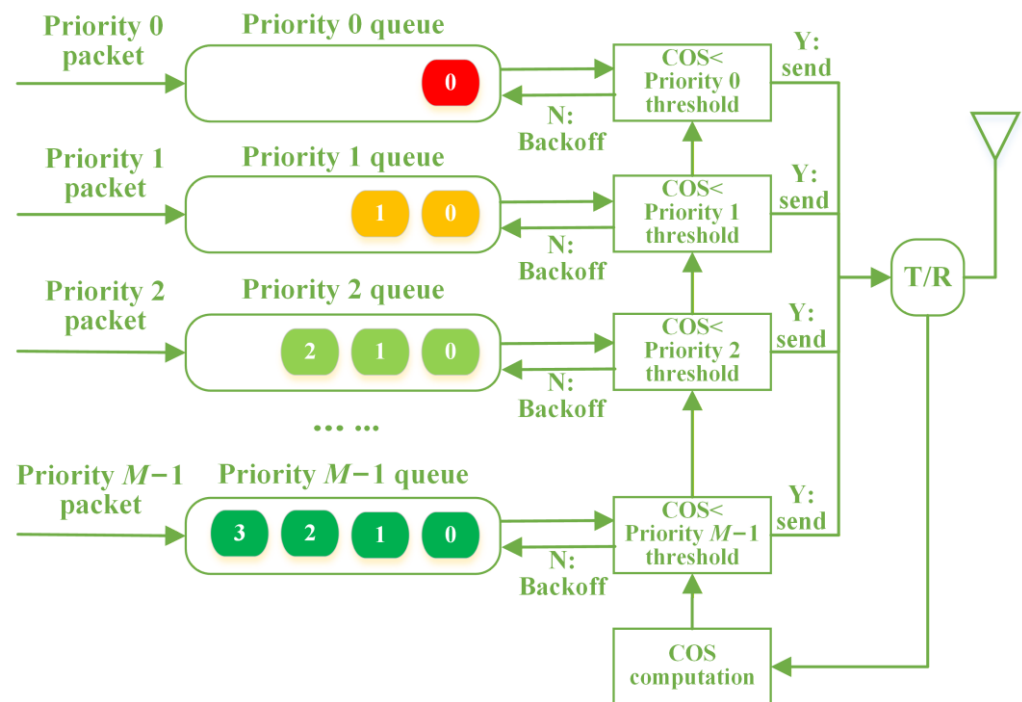


Figure 1. Framework and working mechanism of the SPMA protocol (adapted from [11]).

The above working mechanism is specially designed for the fully connected network shown in Figure 2a. However, when the SPMA protocol is applied to the multi-hop network shown in Figure 2b, its inherent design defects gradually emerge. Existing studies have pointed out that the channel load varies among different nodes in a multi-hop network, and the transmission decision should use the COS of the receiving node of the head-of-line packet instead of the COS counted by the sending node itself [12–14]. Existing schemes generally parse the corresponding COS from HELLO packets periodically broadcast by neighboring nodes at the network layer.

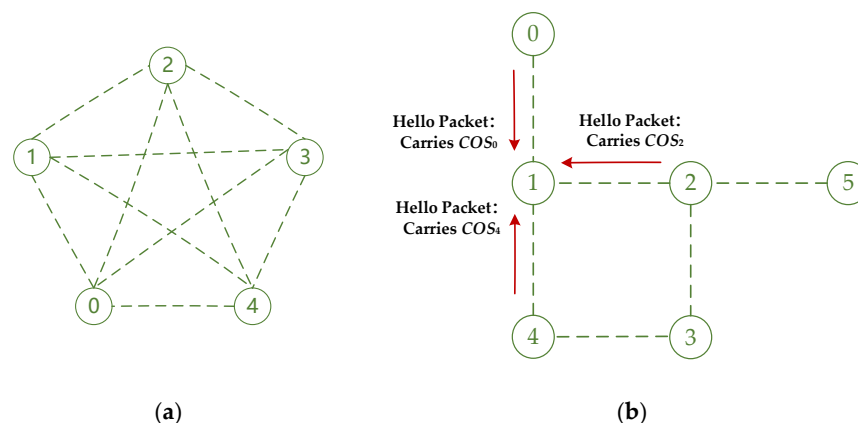


Figure 2. Fully connected network and multi-hop network. (a) Fully connected network. (b) Multi-hop network.

Although this method improves the performance of SPMA in multi-hop networks to a certain extent, its design idea is still limited to the characteristics of fully connected networks and ignores the significant differences from multi-hop networks. This paper finds two important defects as follows:

1. The traditional SPMA protocol stores packets with the same priority but different receiving nodes in the same queue and only uses the COS of the receiving node of the head-of-line packet to compare with the priority threshold. This method greatly reduces the possibility of obtaining better transmission opportunities: it can neither fully utilize the channel difference opportunities between different nodes brought by multi-hop networks nor fully utilize the time difference opportunities brought by node mobility, thus easily causing time slot waste or a low transmission success rate.
2. The traditional SPMA protocol adopts the First-In-First-Out (FIFO) queueing mechanism according to packet arrival time. In multi-hop networks, the arrival time cannot reflect the urgency of timeout. The FIFO mechanism is especially unfair to multi-hop forwarding packets, which easily causes a large number of packets to overflow or be discarded due to timeout at several relay central nodes, thus forming network bottlenecks.

To solve the above problems, this paper proposes an SPMA protocol suitable for multi-hop FANETs, named Multi-hop Adaptive SPMA (MA-SPMA). Firstly, to fully utilize the better scheduling opportunities brought by multi-hop communication and mobility, the protocol extends the traditional SPMA protocol, which only maintains M priority queues, to creating a group of M priority queues for each neighbor separately. On this basis, in each transmission time slot, parallel first-round screening is performed on multiple groups of queues according to the traditional priority-based scheduling decision of SPMA to obtain the candidate queue set allowed for transmission. Then, for all packets stored in the candidate queue set, the utility function value of each packet is calculated. The utility function comprehensively considers key factors that directly affect individual services and overall system throughput, such as timeout, priority, the transmission success rate, and remaining hops, and finally selects the packet with the maximum utility function value for transmission. Through the above method, on the premise of inheriting the priority guarantee capability of the traditional SPMA protocol, this paper extends the protocol structure and upgrades the scheduling strategy according to the characteristics of multi-hop networks, thereby achieving significant performance improvement.

The rest of the paper is organized as follows. Section 2 reviews related research on the SPMA protocol. Section 3 analyzes the defects of traditional SPMA and proposes the design of MA-SPMA. Section 4 presents the detailed algorithm and complexity analysis. Section 5 conducts simulation verification. Section 6 discusses future improvements. Section 7 concludes the paper.

2. Related Work

Research on the SPMA protocol mainly focuses on performance analysis and optimization design. For the SPMA protocol in fully connected networks, optimization design mainly focuses on transmission decision and random backoff; for multi-hop networks, optimization mainly focuses on the accurate estimation of channel load.

Performance Analysis. Performance analysis of the SPMA protocol requires comprehensive consideration of the arrival timing characteristics of different priority services and the spatial randomness of node positions. In [15], Zhang et al. combined stochastic geometry and queueing theory to propose a spatio-temporal joint analysis framework, which simultaneously characterizes the spatial interference distribution and the time-domain evolution process of each priority queue in the SPMA network, derives analytical expressions of medium access probability, burst success probability, and packet success probability, quantifies the impact of key parameters on network stability, and highlights the performance advantages of SPMA over traditional CSMA. In [16], Liu et al. modeled the SPMA protocol using fixed-point analysis and M/G/1 queueing theory, defined and calculated the slot transmission probability (STP) under saturated input, and further derived

key performance indicators such as system throughput, average delay, and packet loss rate, clarified the relationship between priority threshold setting and the transmission success rate, and verified that SPMA can maintain stable system throughput while ensuring low delay and a 99% first transmission success rate for the highest-priority service.

Transmission Decision Optimization. Existing research mainly focuses on queue modeling, parameter optimization, and scheduling fairness. In [17], Gao et al. designed a queueing model to analyze protocol performance and proposed a reinforcement-learning-based parameter optimization method. The study constructed a non-preemptive M/M/1/K queueing model, derived packet loss rate and delay analysis formulas for different priority services in SPMA, and designed and implemented the system state, action, reward function, and Q-value function in the Q-learning algorithm based on the percentile scoring criterion. However, this method has many hyperparameters and is difficult to adapt to various traffic scenarios. In [18], Li et al. derived the equation and solution method of slot transmission probability, set low-priority thresholds with the strategy of minimizing reserved resources between priorities, derived the successful message reception probability and established its general relationship with duty cycle, and obtained the threshold setting method for the highest-priority messages. To solve the conflict between maximizing channel utilization and the inter-node priority scheduling mechanism, this study set low-priority thresholds with the minimum threshold difference, effectively solving the threshold configuration problem of the SPMA protocol. In [19], Yang et al. proposed an adaptive credit-based shaper method (ACBS-RL) based on reinforcement learning to balance the transmission performance of full-priority services. This method introduced a Credit-Based Shaper (CBS) into SPMA to provide relatively fair transmission opportunities for multi-service queues by limiting transmission rates; combined with the dynamic characteristics of wireless environments, it used Q-learning-based reinforcement learning to adaptively adjust CBS parameters and improve the comprehensive performance of full-priority queues. In [20], Liu et al. proposed a priority threshold adaptive adjustment strategy for scenarios where the node transmission rate dynamically changes with channel conditions, improving network throughput and reducing end-to-end delay while ensuring the transmission success rate of the highest-priority services.

Backoff Mechanism Optimization. Existing research mainly faces multi-channel adaptation, window adaptation, and intelligent decision-making. In [21], Zhang et al. established a spatio-temporal mathematical model to model and analyze the backoff mechanism of SPMA networks, integrated the backoff process into a discrete-time Markov chain, and characterized the interference impact caused by node spatial distribution using stochastic geometry theory, derived medium access probability, burst success probability, and packet success probability, and revealed the effect of backoff window, backoff probability, and other parameters on network performance under different traffic loads. In [22], Ge et al. proposed a reliable adaptive multiple access protocol (RA-SPMA) based on statistical priority. This protocol introduced window-adaptive backoff to solve the shortcomings of binary exponential backoff in the M/G/1 queueing model, improved real-time performance by real-time management of channel occupancy status in subnets, and dynamically adjusted access thresholds of frame queues with different priorities to achieve adaptive threshold configuration. In [23], Zhang et al. studied the transmission and intelligent backoff strategy of the SPMA protocol and proposed a transmission and backoff method based on Deep Q-Network (DQN-TB). This method includes two sub-networks: the service transmission network sends as many low-priority services as possible without affecting the performance of high-priority services; the backoff decision network determines the appropriate backoff time according to the current channel occupancy rate and its history. Through collaborative optimization of the two sub-networks, indicators such

as overall network throughput, the transmission success rate, and total backoff time are significantly improved.

Channel Load Estimation Optimization in Multi-hop Networks. Accurate estimation of channel load in multi-hop networks is the key to ensuring the scheduling effect of the SPMA protocol. In [12], Li et al. proposed an Exponentially Weighted Moving Average (EWMA)-based channel load rate evaluation method to solve the problem of inaccurate channel load rate estimation affecting priority scheduling in multi-hop networks, designed a fixed-slot statistics and exponential weighting smoothing mechanism, set the statistics slot as packet transmission delay, and adopted a smoothing coefficient to estimate channel occupancy in real time, effectively reducing estimation error and providing a reliable basis for multi-priority transmission decisions. In [13], Sun et al. proposed a cross-layer optimized Distributed Channel Load Sensing SPMA algorithm (DCLS-SPMA) to solve the problem of inaccurate channel load perception and degraded high-priority service transmission performance caused by hidden terminals in multi-hop environments. This algorithm dynamically obtains the ratio of one-hop and two-hop neighbors in real time through the Optimized Link State Routing (OLSR) protocol to correct channel load estimation, effectively improving the delivery rate of high-priority data and differentiated transmission guarantee capabilities of different priority services. In [14], Liu et al. summarized existing channel load statistics for multi-hop networks, including MAC layer message statistics, cross-layer hybrid statistics, and distributed statistics based on broadcast and distance weighting, and analyzed the defects and error sources of each method in high-dynamic topology, heterogeneous nodes, burst services, and hidden terminal scenarios. On this basis, an improved SPMA algorithm based on BiLSTM channel load prediction (BiLSTM-SPMA) was proposed. This algorithm constructs a training dataset based on historical channel load statistics and uses a BiLSTM neural network to predict channel load at the next moment, improving channel utilization and differentiated service capabilities of multi-priority services.

It is worth noting that this work is a significant extension of our preliminary study [11], which proposed a joint clustering and power optimization framework for the SPMA protocol in frequency-constrained UAV swarm networks. That work primarily focused on mitigating severe channel contention through centralized clustering and adaptive power control under quasi-static topologies. However, it did not address the inherent queuing and scheduling defects of the SPMA protocol in general dynamic multi-hop FANETs. To fill this critical gap, this paper fundamentally reengineers the SPMA protocol from the perspectives of queuing architecture and packet scheduling, specifically targeting dynamic multi-hop topologies rather than static clustering scenarios.

Beyond SPMA-specific optimizations, recent research has explored AI-based approaches for MAC protocol design in ad hoc and multi-hop wireless systems. In particular, multi-agent reinforcement learning (MARL) has emerged as a promising paradigm for learning MAC protocols [24–27]. In [24], Valcarce et al. adopted Tabular Q-Learning for UEs to learn a shared MAC protocol in an uplink radio network. In [25], Mota et al. extended this approach by employing MADDPG, where each agent maintains an independent actor network and a shared centralized critic. In [26], Miuccio et al. applied MAPPO to learn generalized MAC protocols and further addressed the feasibility issue of MARL-based solutions by proposing a framework that replaces the omniscient environment with a practical base station that computes rewards based on locally available information. These MARL-based approaches have demonstrated promising simulation results; however, they typically rely on centralized information aggregation and extensive communication overhead during training, which may hinder their practical deployment in resource-constrained and highly dynamic FANETs environments.

3. Problem Analysis and Scheme Design

3.1. Defect Analysis of Traditional SPMA Protocol in Multi-Hop Networks

The first research motivation of this paper is to discover the irrationality of the traditional SPMA protocol that only uses priority as the basis for packet classification and storage in multi-hop networks. As shown in Figure 3, all priority 0 packets entering Node 1 are stored in the priority 0 queue of this node. In each transmission time slot, the traditional SPMA protocol performs transmission decision on the head-of-line packet. In Figure 3, the next-hop address of the head packet Packet 0 is Node 2, so the COS of Node 2 is compared with the threshold of the priority 0 queue. Since the channel load of Node 2 is the heaviest, the comparison result is not to transmit, and the priority 0 queue enters the backoff state, resulting in no packets in the queue being able to obtain transmission opportunities before the end of backoff. However, the COS of different receiving nodes is different. If packets are stored separately according to different next-hop receiving addresses on the basis of priority classification, Packet 1 can be queued at the head of the priority 0 queue to Node 0. At this time, since the channel load of Node 0 is much lower than the threshold of priority 0, the packet can obtain transmission opportunities.

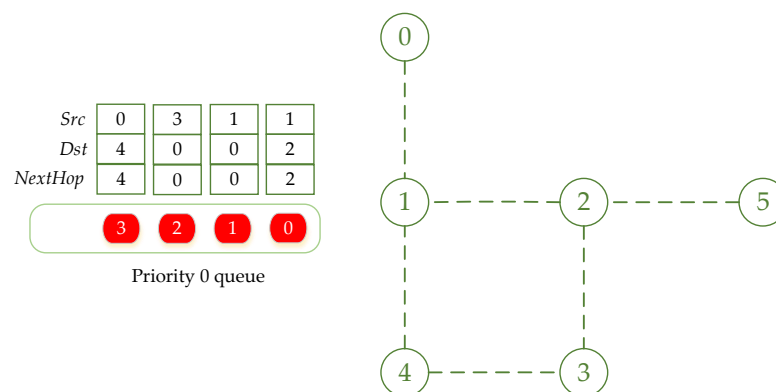


Figure 3. Packet storage of priority queues in a multi-hop network.

The second research motivation of this paper is to discover the irrationality of the traditional SPMA protocol's First-In-First-Out (FIFO) queueing method according to packet arrival time. The traditional SPMA protocol places packets with the same priority into the same priority queue according to their arrival time at this node. In a fully connected network, since there is only one hop, an earlier arrival time is equivalent to being closer to timeout, so it is reasonable to transmit first. However, taking the priority 0 queue of Node 1 as shown in Figure 3, according to the FIFO method, locally generated packets (such as Packet 0 with $Src = 1$ and $Dst = 2$, and Packet 1 with $Src = 1$ and $Dst = 0$) are queued in the front, while packets to be forwarded generated by other nodes and arriving at this node after one or more hops (such as Packet 2 with $Src = 3$ and $Dst = 0$, and Packet 3 with $Src = 5$ and $Dst = 0$) are queued behind. Although these two forwarding packets arrive later, they are more likely to be discarded by the relay node due to timeout.

3.2. Solution and Mechanism Design

This paper proposes a multi-hop adaptive SPMA protocol (MA-SPMA) for multi-hop FANETs. The protocol includes two core mechanisms: the Neighbor-Priority Two-Dimensional Queueing (NPTQ) and the Priority-Utility Dual-round Decision (PUDD), which can effectively solve the above inherent design defects of traditional SPMA in multi-hop networks.

The overall framework of the MA-SPMA protocol is shown in Figure 4. For any node i in the network, the MA-SPMA protocol layer includes $N(i)$ groups of priority queues working in parallel, each with M queues, where $N(i)$ is the number of neighbors of node i , and M is the number of priorities. All packets stored in group j have the next-hop node as the j -th neighbor $Neighbor(j)$ of node i . Whenever node i receives a HELLO packet broadcast by a new neighbor, it creates M new priority queues for that node in the MA-SPMA protocol layer and periodically updates the channel load status of that node by parsing the COS carried in the HELLO packet.

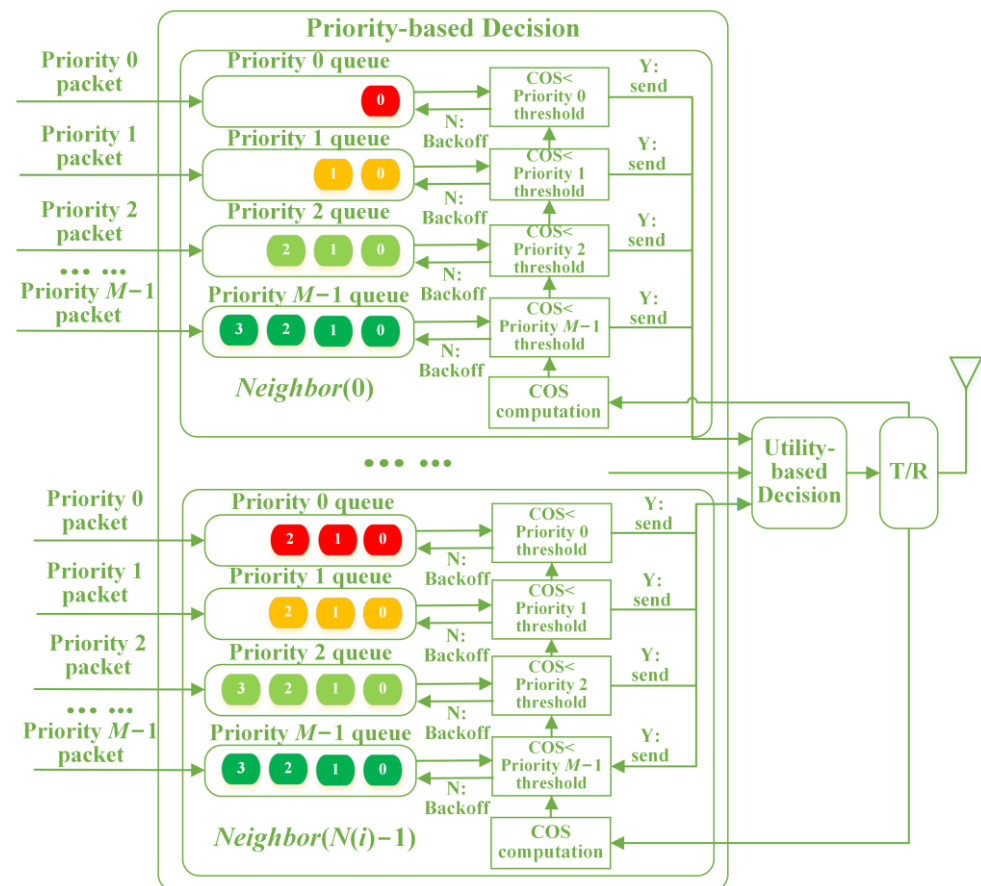


Figure 4. Overall framework of the MA-SPMA protocol.

In addition to the above framework, MA-SPMA inherently alleviates the starvation of low-priority services, which is a critical issue in traditional SPMA under heavy traffic loads. This is achieved through two mechanisms. First, the NPTQ mechanism stores packets in a two-dimensional manner according to the next-hop neighbor and priority. Even if a low-priority queue for a particular next-hop neighbor enters backoff due to channel busyness, other queues of the same priority destined for different neighbors may still be scheduled. This avoids the “chain blocking” problem in traditional SPMA, where a single head-of-line packet blocks the entire priority queue from being served. Second, the PUDD mechanism selects packets in the second round based on a utility function that jointly considers normalized delay, priority, and end-to-end transmission success probability. For low-priority packets that have been waiting in the queue for an extended period and are approaching timeout, their normalized delay increases, thereby raising their utility value and granting them transmission opportunities in the second-round selection. This effectively prevents low-priority traffic from being persistently blocked until timeout. A detailed description of the utility function is provided below.

Based on NPTQ grouping, when any packet pkt arrives at the network layer of node i , the network layer stores pkt into the priority m queue created by the MA-SPMA protocol layer for $NextHop$ according to the next-hop node $NextHop$ and priority m (ranging from 0 to $M - 1$, where 0 represents the highest priority) of pkt . During the transmission decision in each time slot, the MA-SPMA protocol performs the first-round decision on $N(i)$ groups simultaneously according to the judgment process of the traditional SPMA protocol to obtain a candidate queue set and then performs the second-round decision on all packets in the candidate queue based on the utility function to select the packet with the maximum utility value for transmission.

The utility function $U(pkt)$ of any packet pkt in the candidate queue is defined as follows:

$$U(pkt) = \left(\frac{t_{elapsed}(pkt)}{T_{timeout}(pkt)} \right)^{m+1} \times P_s(pkt)^{h_{rem}(pkt)}, \quad (1)$$

where $T_{timeout}(pkt)$ is the timeout of the priority to which pkt belongs and $t_{elapsed}(pkt)$ is the elapsed delay of pkt , i.e., the current time minus the generation time of pkt at its source node. Since timeout packets are discarded, the normalized delay satisfies $\frac{t_{elapsed}(pkt)}{T_{timeout}(pkt)} < 1$. The exponential term $(m + 1)$ ensures that packets closer to timeout have larger utility values under the same priority, and packets with higher priority have larger utility values under the same normalized delay. $P_s(pkt)$ is the transmission success rate of pkt sent to the next-hop node, and $h_{rem}(pkt)$ is the remaining hops of pkt , satisfying $h_{rem}(pkt) \geq 1$. $P_s(pkt)^{h_{rem}(pkt)}$ can be regarded as the end-to-end transmission success rate of pkt from current node i to the destination node; the larger the value, the higher the probability that pkt successfully arrives at the destination node. Therefore, $U(pkt)$ comprehensively considers the normalized delay, priority, and end-to-end transmission success rate of the packet, preferentially transmitting packets with large normalized delay, high priority, and a high end-to-end transmission success rate, balancing the QoS of individual services and the throughput of the entire network.

We note that the utility function in Equation (1) involves two design choices that merit further clarification. First, the exponential term $(m + 1)$ serves to amplify the influence of priority on the utility value while maintaining a strict priority ordering. By using the normalized delay as the base and raising it to a priority-dependent exponent greater than 1, a higher-priority packet achieves a dominantly larger utility than a lower-priority one under the same normalized delay. This design adheres to the core principle of the SPMA protocol, which prioritizes the QoS of high-priority services. Second, the multiplicative factor $P_s(pkt)^{h_{rem}(pkt)}$ intentionally penalizes packets with poor next-hop transmission success probability or a large number of remaining hops. This prevents nodes from blindly forwarding packets over unreliable links, which would otherwise waste channel resources and exacerbate network congestion. It represents a deliberate trade-off between individual packet delivery and overall network stability. Meanwhile, the normalized delay term $t_{elapsed}(pkt)/T_{timeout}(pkt)$ increases for packets that have been waiting for a long time, thereby raising their utility value and preventing multi-hop flows from being permanently starved under persistently poor channel conditions. The interaction between these two terms ensures that the scheduler balances urgency, priority, and transmission reliability in a coherent manner.

When only considering packet transmission failure caused by collision, the transmission success rate $P_s(pkt)$ of the packet does not require actual measurement and can be directly estimated using the following formula [11]:

$$P_s(pkt) = \sum_{n=[N_b/2]}^{N_b} C_{N_b}^n P_{bs}^n (1 - P_{bs})^{N_b-n}, \quad (2)$$

where $P_{bs} = \exp\left(-\frac{N_b \cdot \overline{COS}_{NextHop}}{W_T \cdot N_f}\right)$, N_b is the number of data frames that the packet is split into at the physical layer, N_f is the number of available channels, W_T is the channel detection window length for counting COS, and $\overline{COS}_{NextHop}$ is the estimated COS value of node *NextHop*. Obviously, as the only variable in the formula of $P_s(pkt)$, accurate estimation of COS significantly affects protocol performance. The MA-SPMA protocol adopts the following exponential smoothing method:

$$\overline{COS}_{NextHop}(t) = \alpha \cdot COS_{NextHop}(t) + (1 - \alpha) \cdot \overline{COS}_{NextHop}(t - 1), \quad (3)$$

where $COS_{NextHop}(t)$ is the instantaneous COS value of node *NextHop* obtained by node *i* at time *t*, equal to the total number of received and sent data frames of the physical layer of node *NextHop* in the latest channel detection window, attached to the HELLO packet broadcast by the network layer of the node; $\overline{COS}_{NextHop}(t)$ is the smoothed estimated COS value at time *t*; $\overline{COS}_{NextHop}(t - 1)$ is the smoothed estimated COS value at the previous time slot; α is the smoothing coefficient ranging from 0 to 1; and a larger α means a more prominent influence of the instantaneous value. In the following simulations, α is set to 0.7, which balances tracking responsiveness and noise suppression, providing timely COS updates for highly dynamic FANET environments.

According to the above scheduling rules, taking the transmission decision of Node 1 in Figure 5 as an example, first, the priority-based decision mechanism adopted in the traditional SPMA protocol evaluates all neighbor groups simultaneously. At this time, the priority 2 queue of *Neighbor(0)* and the priority 1 queue of *Neighbor(2)* enter the candidate queue. In the second-round decision, for all four packets stored in these two queues, the utility value of each packet is calculated according to Equation (1), and then the packet with the maximum utility value (Packet 0 located in the priority 2 queue of *Neighbor(0)*) is selected for transmission.

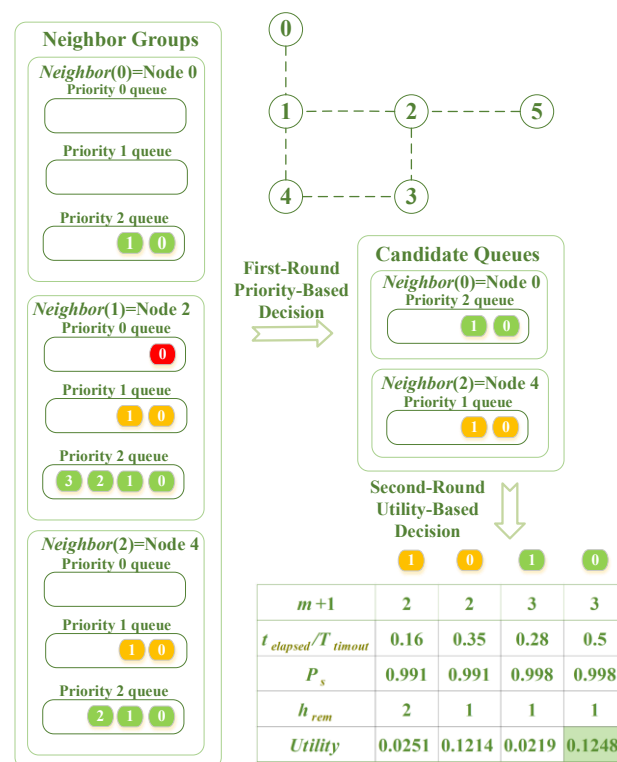


Figure 5. Example of the Priority-Utility Dual-round Decision Mechanism of MA-SPMA.

4. Algorithm Design

The MA-SPMA algorithm is divided into two stages in sequence: (1) in NPTQ-based packet queueing, grouping and queue are determined according to next-hop neighbor and priority. (2) In the PUDD-based transmission decision, in the first round, all neighbor groups perform parallel priority-based transmission decisions to generate candidate queues; in the second round, the packet with the optimal utility function is selected from the candidate queues. The implementation algorithms of these two stages are described in detail below.

4.1. Algorithm 1: NPTQ-Based Packet Queueing

Algorithm 1 describes how to place a packet into the corresponding queue according to its next-hop node and priority when the node receives a packet (locally generated or forwarded from a neighbor). In Step 2, the next-hop address is obtained by querying the network layer routing table according to the destination address parsed from the packet header. In Steps 3–4, the grouping and queue are determined according to the next-hop node and priority of the packet. In Steps 6–10, if the packet has timed out or the queue is full, the packet is discarded; otherwise, it is inserted into the queue.

Algorithm 1: NPTQ-based Packet Queueing

Input: Packet pkt arriving at node i

Output: Packet enqueued or discarded

```

1: Parse  $m, Dst, t_{gen}$  from  $pkt$  header
2: Query routing table according to  $Dst$  to get  $NextHop$ 
3: Map  $NextHop$  to group index  $j$ 
4: Locate target queue  $Q_{j,m}$  according to  $j$  and  $m$ 
5:  $t_{elapsed}(pkt) \leftarrow t_{now} - t_{gen}$ 
6: if  $t_{elapsed}(pkt) > T_{timeout}(pkt)$  or  $is\_full(Q_{j,m})$  then
7:   Discard  $pkt$ 
8:   return
9: end if
10: Insert  $pkt$  into  $Q_{j,m}$ 

```

4.2. Algorithm 2: PUDD-Based Transmission Decision

Algorithm 2 describes how a node selects a packet with the maximum utility value from multiple neighbor groups for transmission in each time slot. Steps 1–15 perform parallel priority-based decisions on multiple neighbor groups using the traditional SPMA protocol simultaneously, adding all non-empty, backoff-expired queues with COS below the transmission threshold to the candidate queue set. In this process, if the queue is non-empty and backoff-expired but COS is not less than the transmission threshold, the queue is set to re-execute backoff with basic window length W_{base} (Steps 9–12). Steps 16–31 perform the second-round transmission decision on all packets in the candidate queue based on the utility function. For each packet, information is first parsed from its header (Step 21) to obtain the delay, next-hop node and current COS estimate (Steps 22–24). Then, the transmission success rate is calculated using Equation (2) (Step 25), the utility value is calculated using Equation (1) (Step 26), and finally the packet with the maximum utility value is selected for transmission (Steps 29–30) and removed from the queue (Step 31).

Algorithm 2: PUDD-based Transmission Decision**Input:** All grouped queues of node i **Output:** Transmit packet with maximum utility or no transmission

```

1: candidateQueues  $\leftarrow \emptyset$ 
2: for  $j \leftarrow 0$  to  $N(i) - 1$  do
3:   Map group index  $j$  to next-hop node  $NextHop$ 
4:   Update COS estimate  $\overline{COS}_{NextHop}$  using Equation (3)
5:   for  $m \leftarrow 0$  to  $M - 1$  do
6:     if  $Q_{j,m} \neq \emptyset$  and backoff_expire( $Q_{j,m}$ ) and  $\overline{COS}_{NextHop} \leq Th_m$  then
7:       Add  $Q_{j,m}$  to candidateQueues
8:       break
9:     else if  $Q_{j,m} \neq \emptyset$  and backoff_expire( $Q_{j,m}$ ) and  $\overline{COS}_{NextHop} > Th_m$  then
10:       $t_{backoff} \leftarrow \text{Random}[0, W_{base} \times (m + 1)]$ 
11:      Execute backoff for  $Q_{j,m}$  with duration  $t_{backoff}$ 
12:      break
13:     end if
14:   end for
15: end for
16: if candidateQueues ==  $\emptyset$  then
17:   return
18: end if
19: for each  $Q \in$  candidateQueues do
20:   for each  $pkt \in Q$  do
21:     Parse  $m, Dst, h_{rem}, t_{gen}$  from  $pkt$  header
22:      $t_{elapsed}(pkt) \leftarrow t_{now} - t_{gen}$ 
23:     Query routing table according to  $Dst$  to get  $NextHop$ 
24:     Update COS estimate  $\overline{COS}_{NextHop}$  using Equation (3)
25:     Calculate  $P_s(pkt)$  using Equation (2) based on  $\overline{COS}_{NextHop}$ 
26:     Calculate  $U(pkt)$  using Equation (1) based on  $h_{rem}, t_{elapsed}(pkt)$  and  $P_s(pkt)$ 
27:   end for
28: end for
29:  $pkt_{best} \leftarrow \text{argmax}\{U(pkt)\}$ 
30: Transmit  $pkt_{best}$ 
31: Remove  $pkt_{best}$  from queue

```

4.3. Algorithm Complexity Analysis

This section analyzes MA-SPMA from time complexity and space complexity and compares it with the traditional SPMA protocol.

4.3.1. Time Complexity

The time cost of MA-SPMA mainly comes from two parts:

1. NPTQ-based packet queueing (Algorithm 1): routing table query, group mapping, queue location, and timeout judgment are all constant operations, complexity $O(1)$.
2. PUDD-based transmission decision (Algorithm 2): in the first round of the parallel decision, each candidate queue is checked from high priority to low priority to find eligible queues. Each group checks at most M priorities, so the total number of checks does not exceed traversing $N(i)$ neighbor groups and M priorities, complexity $O(N(i) \cdot M)$. In the second round of utility optimization, utility values are calculated for all packets in the candidate queues, and the maximum value is selected. The maximum number of candidate queues is $N(i)$. Let the length of each priority queue be L ;

then, the complexity of calculation and optimization is $O(N(i) \cdot L)$. Therefore, the total time complexity of Algorithm 2 is $O(N(i) \cdot M + N(i) \cdot L) = O(N(i) \cdot (M + L))$.

In summary, the total time complexity of MA-SPMA per time slot is $O(1 + N(i) \cdot (M + L))$. Since M and L are constants, it can be simplified to $O(N(i))$, which is linearly related only to the number of neighbor nodes and can meet the real-time processing requirements of UAV nodes with limited computing resources.

4.3.2. Space Complexity

The space cost of MA-SPMA mainly includes the following:

1. Queue storage: each node maintains $N(i) \cdot M$ priority queues, each with length L , space complexity $O(N(i) \cdot M \cdot L)$.
2. Routing table and neighbor information: storing addresses and COS values of $N(i)$ neighbors, space complexity $O(N(i))$.
3. Auxiliary variables (including candidate queues, temporary utility values, etc.): $O(N(i))$.

Therefore, the total space complexity is $O(N(i) \cdot M \cdot L) + O(N(i)) + O(N(i)) = O(N(i) \cdot M \cdot L)$. Since M and L are constants, it can be simplified to $O(N(i))$, which is linearly related only to the number of neighbor nodes and suitable for memory-constrained UAV platforms.

4.3.3. Complexity Comparison with Traditional SPMA Protocol

The traditional SPMA protocol only checks one non-empty highest-priority queue per time slot, with time complexity $O(M)$; it only maintains M queues, each with length L , space complexity $O(M \cdot L)$. Although the time and space complexity of MA-SPMA are higher than those of the traditional SPMA protocol, its overhead is linearly related only to the local neighbor count $N(i)$ and does not grow with the total number of network nodes. It can run distributedly and in real time on UAV nodes with limited computing and storage resources, adapting to multi-hop and dynamic topology scenarios.

5. Simulation Verification

To verify the effectiveness of the proposed algorithm, two representative algorithms are selected for performance comparison under different priority service allocation ratios and network topologies:

- DCLS-SPMA [13]: dynamically adjust the priority threshold by calculating the load factor through OLSR;
- BiLSTM-SPMA [14]: predict channel load using a BiLSTM neural network.

5.1. Simulation Scenario

Network Topology. A multi-hop FANET scenario with multiple UAV nodes is built using MATLAB R2021a. Figure 6 divides all nodes into four overlapping clusters. Member nodes in each cluster are directly connected to the cluster head node in one hop, and adjacent clusters are connected through gateway nodes in the overlapping area to provide multi-hop forwarding paths between clusters.

To simulate the dynamic characteristics of UAV nodes, all nodes adopt the Reference Point Group Mobility (RPGM) model. Each cluster corresponds to a logical group; member nodes in the group move around the cluster head, and the cluster head moves within a limited area according to the random waypoint model. The position of member nodes relative to the cluster head follows a uniform distribution, and the movement range is limited by the intra-cluster communication radius to ensure stable one-hop connectivity with the cluster head. Gateway nodes belong to multiple groups simultaneously, and their movement is jointly constrained by the cluster heads of their affiliated groups to ensure

that overlapping areas persist during movement and avoid inter-cluster link interruption caused by node separation. Through the above parameter configuration of the mobility model, the number of clusters, nodes included in each cluster, and gateway nodes of adjacent clusters in the topology shown in Figure 6 remain unchanged during the entire simulation period, facilitating the comparison and analysis of protocol performance.

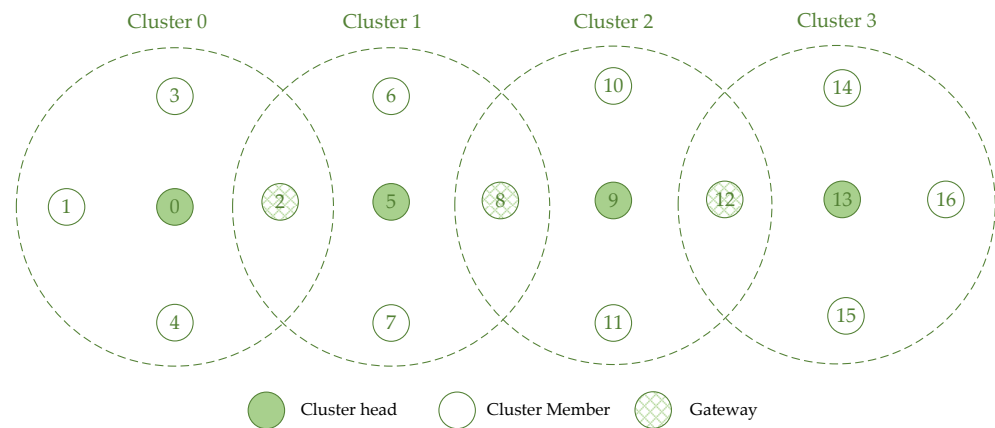


Figure 6. Multi-hop network topology of the FANETs.

Parameter Settings. Basic simulation parameters are shown in Table 1. All simulation results presented in this paper are averaged over 10 independent runs with different random seeds. For each run, the simulation duration is 100,000 time slots. Three priority services are set in the simulation. Each node independently generates packets. The per-node total service rate is varied from 0 to 5 Mbps and is allocated to the priority queues supported by the node according to the ratios of 1:1:1 or 1:2:4 [19]. All 17 nodes generate priority 0 and priority 1 service, while only 4 nodes generate priority 2 service. In the simulations of Sections 5.2.1–5.2.3, the node mobility speed is set to 20 m/s. To evaluate the protocol robustness against topology dynamics, two additional mobility speeds, 40 m/s and 60 m/s, are considered in addition to the default 20 m/s.

Table 1. Basic simulation parameters.

Parameter	Value	Parameter	Value
Number of Nodes	17	Mobility Model	RPGM
Simulation Duration	100,000 slots	Moving Speed	20/40/60 m/s
Communication Distance	10 km	Routing Protocol	OLSR
Cluster Radius	10 km	Packet Length	100 bytes
Number of Channels	1	Priority Queue Length	10 packets
Transmission Rate	20 Mbps	Number of Priorities	3
Slot Duration	10 μ s	Priority Service Allocation Ratio	1:1:1/1:2:4

Priority service parameters are shown in Table 2. Packets of each service are generated according to an independent Poisson distribution. Priority 0 corresponds to HELLO and TC packets of the OLSR routing protocol, periodically sent by all 17 nodes for network maintenance and COS information interaction. Priority 1 is a single-hop application service generated by all 17 nodes. Priority 2 is a multi-hop application service generated only by 4 gateway nodes (cluster heads) and forwarded to the target node in 3 hops. For example, in Figure 6, Node 0 in Cluster 0 sends to Node 6 in Cluster 1 through Node 2 and Node 5.

Table 2. Priority service parameters.

Priority	Timeout	Tx Success Rate	Hops	Node Count
0	≤ 2 ms	$\geq 99\%$	1	17
1	≤ 10 ms	$\geq 95\%$	1	17
2	≤ 50 ms	$\geq 90\%$	3	4

In addition, the proposed algorithm and the two comparison algorithms differ in priority threshold measurement, channel detection window length, backoff time calculation, etc. The method used in this paper is as follows:

- The highest-priority threshold is determined following the general method of the SPMA protocol: continuously increase the channel load from 0 until the packet transmission success rate drops from 100% to 99%; the channel occupancy rate calculated according to Equation (3) during this process is the highest-priority threshold.
- According to the above method, the sliding channel detection window length is set to 10 ms in the simulation, and the highest-priority threshold obtained after smoothing statistics is 0.1. The transmission thresholds of the other two priorities are set to 0.08 and 0.06, respectively, following two general principles: they must be strictly lower than the highest-priority threshold and decrease monotonically with decreasing priority. The difference between adjacent thresholds (e.g., 0.02 between 0.08 and 0.06) is suggested to be larger than the standard deviation of COS estimation (approximately 0.018 in our simulations) to prevent lower-priority traffic from preempting higher-priority transmission opportunities, while avoiding excessively large gaps that would create idle periods in channel access. For instance, when the COS is 0.07, even if priorities 0 and 1 have no packets to send, the lowest-priority traffic still cannot transmit because the COS exceeds its threshold of 0.06.
- The backoff time is calculated as $t_{\text{backoff}} = \text{Random}[0, W_{\text{base}} \times (m + 1)]$, where the basic backoff window length $W_{\text{base}} = 8$, and m takes 0, 1, 2 in descending order of priority.

The settings of the other two algorithms are consistent with their respective references.

Routing update and failure handling. In our simulations, routing maintenance is performed by the OLSR protocol. When topology changes cause link failures or route changes, the OLSR MPR (Multipoint Relay) mechanism rapidly detects link breaks through the absence of HELLO messages and updates the network topology via TC (Topology Control) message flooding. In MA-SPMA, when a route changes, newly arriving or buffered packets are assigned to new neighbor queues based on the updated routing table. Packets that cannot be forwarded before their timeout are discarded. This simulation framework naturally handles route changes through OLSR's inherent route update mechanism.

Three performance metrics are used to evaluate the effectiveness of the proposed MA-SPMA algorithm:

- Network throughput: total successfully transmitted data in the network divided by simulation time, reflecting overall network capacity.
- End-to-end transmission success rate: the ratio of packets successfully received by the destination node to packets sent by the source node, reflecting the transmission reliability of each priority service.
- End-to-end delay: the time elapsed from generation to successful reception at the destination node for a successfully transmitted packet, reflecting real-time performance.

5.2. Simulation Results and Analysis

5.2.1. End-to-End Transmission Success Rate

Figure 7a–c show the end-to-end transmission success rates of the three priorities when the priority service allocation ratio is 1:1:1. Compared with DCLS-SPMA, MA-SPMA improves the transmission success rates of the three services by up to 38.82, 17.57, and 16.59 percentage points, respectively. Compared with BiLSTM-SPMA, MA-SPMA achieves similar performance on priorities 0 and 1 but significantly improves the multi-hop service priority 2 by up to 26.62 percentage points.

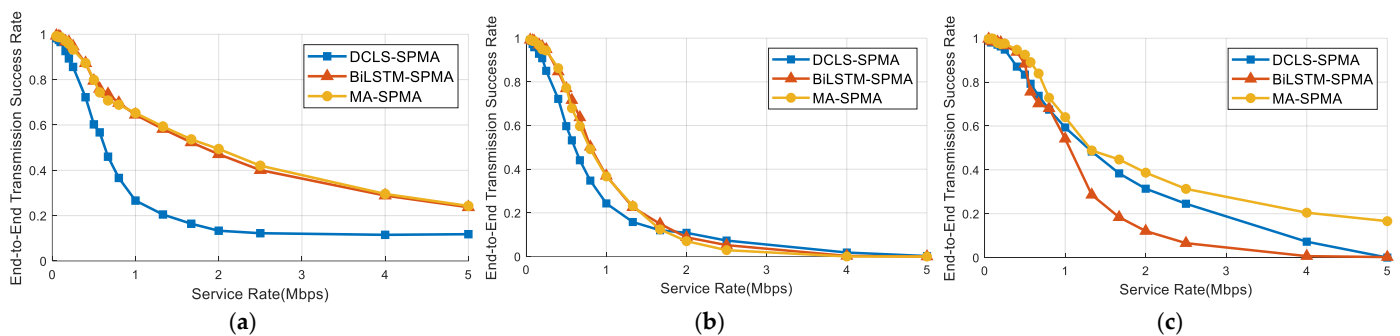


Figure 7. End-to-end transmission success rate under priority service allocation ratio 1:1:1. (a) Priority 0. (b) Priority 1. (c) Priority 2.

The reason is that DCLS-SPMA has a short random backoff value independent of priority, allowing more transmission opportunities for low-priority services while reducing opportunities for priority 0. Coupled with the strict timeout requirement of priority 0 (≤ 2 ms), many packets are discarded due to timeout during queueing, resulting in a much lower transmission success rate than the other two algorithms. BiLSTM-SPMA adopts the opposite strategy: higher priority corresponds to shorter backoff time, so high-priority services obtain more transmission opportunities, and their success rates are close to MA-SPMA. However, the lowest-priority service (priority 2) has the fewest transmission opportunities and requires multi-hop forwarding, leading to serious congestion at relay nodes and discards due to queue overflow. The backoff window length of MA-SPMA is also related to priority, but by preferentially transmitting packets with the highest utility value, it achieves better opportunistic scheduling, improves channel utilization, and greatly reduces packet loss caused by timeout or queue overflow.

Figure 8a–c show the end-to-end transmission success rates of the three priorities when the priority service allocation ratio is 1:2:4. Compared with Figure 7, the service proportion of priority 0 decreases from 1/3 to 1/7, and that of priority 2 increases from 1/3 to 4/7. Therefore, at the same service rate, the transmission success rate of priority 0 increases in each algorithm, while that of priority 2 decreases significantly.

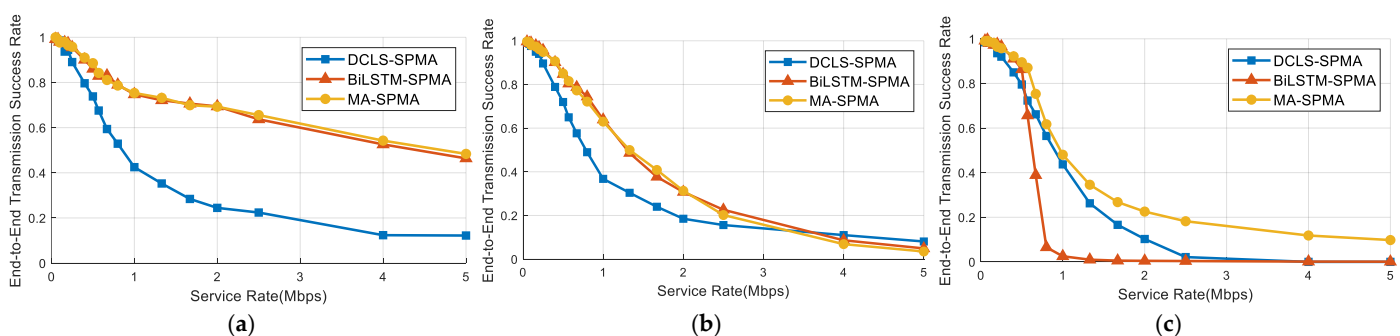


Figure 8. End-to-end transmission success rate under priority service allocation ratio 1:2:4. (a) Priority 0. (b) Priority 1. (c) Priority 2.

Compared with DCLS-SPMA, MA-SPMA consistently outperforms in the transmission success rate of priority 0 and priority 2 across the entire service rate range, with maximum improvements of 44.8 and 16.06 percentage points, respectively. For priority 1, MA-SPMA performs better before the rate reaches 4 Mbps, with a maximum improvement of 26.2 percentage points, but slightly worse after 4 Mbps (3.82 percentage points lower at 4 Mbps, 4.40 at 5 Mbps). The reason is that when the service rate increases beyond 4 Mbps, priority 2 under DCLS-SPMA suffers severe congestion at relay nodes; most packets are discarded due to queue overflow and timeout, and transmission opportunities are almost entirely transferred to the two higher-priority services. Under MA-SPMA, priority 2 always participates in competition, so the transmission opportunities of priority 1 are relatively reduced.

Compared with BiLSTM-SPMA, there is no significant difference in the transmission success rate of priorities 0 and 1, similar to Figure 7. However, the improvement in priority 2 is very significant, reaching up to 55.16 percentage points, indicating that the proposed optimization has more prominent performance advantages in scenarios with a large number of multi-hop forwarding packets.

5.2.2. Network Throughput

Figure 9a,b show the network throughput performance of the three algorithms under two priority service allocation ratios. It can be seen from the figures that the network throughput of each algorithm gradually increases with the increase in the service rate initially, reaches the peak when the service rate reaches the network saturation point, and then no longer increases or even begins to decline. For example, in Figure 9a, DCLS-SPMA peaks at 2.20 Mbps when the service rate reaches 0.8 Mbps and then decreases; BiLSTM-SPMA peaks at 3.36 Mbps at 1 Mbps and then decreases; and MA-SPMA peaks at 3.82 Mbps at 2 Mbps and remains basically stable thereafter.

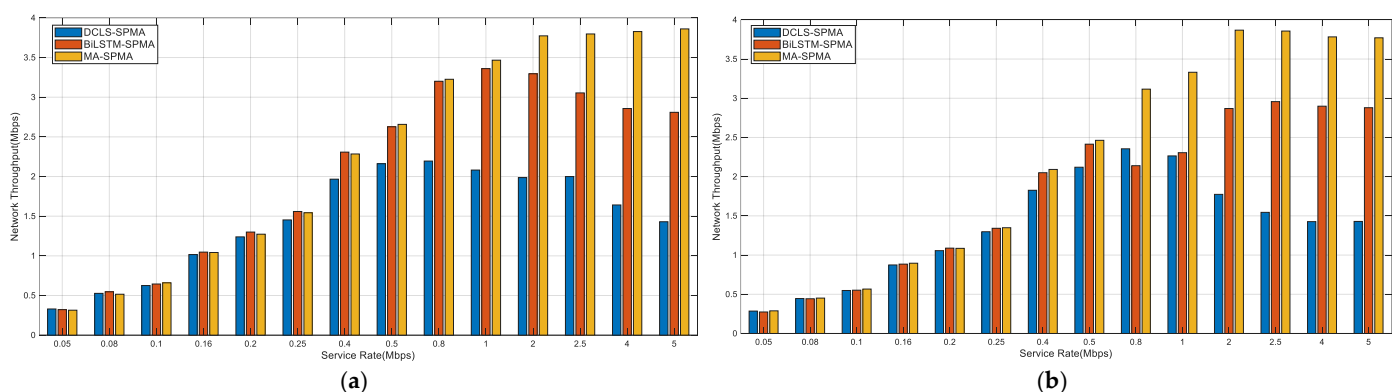


Figure 9. Network throughput under different priority service allocation ratios. (a) Priority service allocation ratio 1:1:1. (b) Priority service allocation ratio 1:2:4.

When the allocation ratio is 1:1:1, compared with DCLS-SPMA and BiLSTM-SPMA, MA-SPMA improves network throughput by up to 170.05% and 37.44%, respectively. When the ratio is 1:2:4, the improvements are up to 165.15% and 45.62%, respectively. The reason is that the two comparison algorithms have extremely limited optional ranges during scheduling, only making transmission decisions based on the channel load of the unique head-of-line packet's receiving node in the current priority queue. In contrast, the proposed algorithm can select from all neighbors, greatly expanding the optional range and flexibility. It can fully utilize real-time changes in network topology and channel load for more efficient opportunistic scheduling, significantly reducing packet queue overflow and timeout and thereby enhancing overall network capacity.

5.2.3. End-to-End Delay

It should be noted that end-to-end delay is computed only for successfully delivered packets. To avoid misleading interpretations when the transmission success rate is very low, we only present delay results for scenarios where the end-to-end transmission success rate exceeds a threshold (5% in our simulations). Below this threshold, the surviving sample size is insufficient to produce statistically meaningful delay estimates.

Figure 10a–c show the end-to-end delay curves of the three priorities under the 1:1:1 traffic allocation ratio. For priority 0, DCLS-SPMA achieves the lowest delay, while MA-SPMA and BiLSTM-SPMA exhibit comparable performance with a maximum difference of approximately 0.18 ms. For priority 1, DCLS-SPMA achieves the lowest delay within its valid range (up to 2.5 Mbps); MA-SPMA is slightly higher than BiLSTM-SPMA with a maximum difference of approximately 1.49 ms at 1.67 Mbps. For priority 2 (multi-hop traffic), MA-SPMA demonstrates significant delay advantages over BiLSTM-SPMA within the valid rate range (up to 2.5 Mbps), with reductions of 40.84 ms at 1.67 Mbps and 14.59 ms at 2 Mbps.

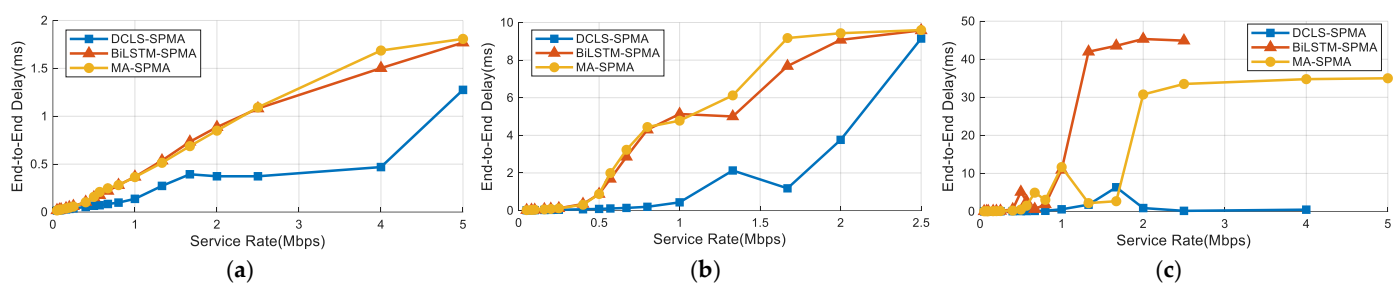


Figure 10. End-to-end delay under priority service allocation ratio 1:1:1. (a) Priority 0. (b) Priority 1. (c) Priority 2.

Compared with DCLS-SPMA, MA-SPMA exhibits higher delay across all three priorities: up to 1.22 ms for priority 0, 7.99 ms for priority 1, and 31.72 ms for priority 2. This is because DCLS-SPMA adopts a smaller random backoff value, allowing faster channel access, but at the cost of significantly reduced transmission success rates. In contrast, MA-SPMA's utility-based scheduler jointly considers delay, priority, and transmission success probability. When delays are comparable, packets with higher priority or better success probability are prioritized, which inevitably increases delay for some packets but substantially improves overall transmission reliability and throughput.

Figure 11a–c show the end-to-end delay curves of the three priorities under the 1:2:4 traffic allocation ratio. As in Figure 10, delay results are presented only for traffic rates where the transmission success rate exceeds 5%.

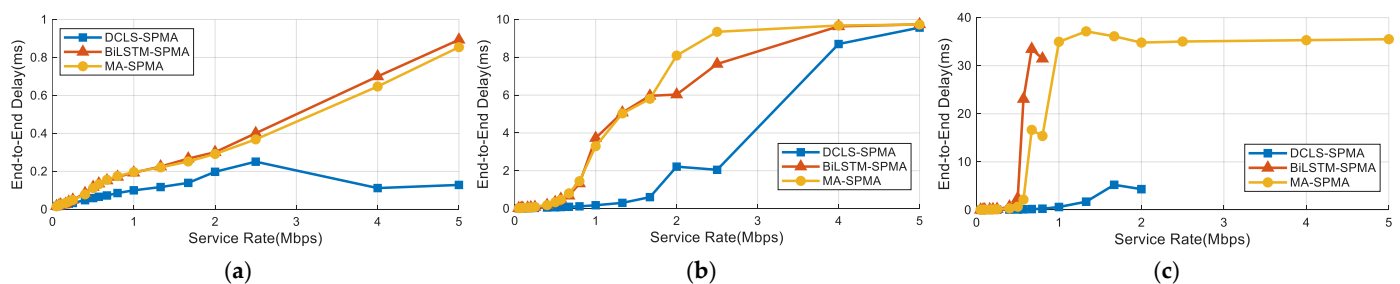


Figure 11. End-to-end delay under priority service allocation ratio 1:2:4. (a) Priority 0. (b) Priority 1. (c) Priority 2.

For Priority 0, DCLS-SPMA achieves the lowest delay, while MA-SPMA slightly outperforms BiLSTM-SPMA by up to 0.05 ms. For priority 1, DCLS-SPMA again achieves the lowest delay; MA-SPMA is slightly higher than BiLSTM-SPMA with a maximum difference of approximately 2.06 ms at 2 Mbps. For priority 2 (multi-hop traffic), BiLSTM-SPMA delay measurements are valid only up to 0.8 Mbps, beyond which its success rate falls below 5%. Within this valid range, MA-SPMA outperforms BiLSTM-SPMA with a maximum reduction of approximately 16.07 ms at 0.8 Mbps (BiLSTM-SPMA: 31.46 ms, MA-SPMA: 15.39 ms).

Compared with DCLS-SPMA, MA-SPMA exhibits higher delay across all three priorities: up to 0.73 ms for priority 0, 7.30 ms for priority 1, and 31.72 ms for priority 2. As in the 1:1:1 case, this trade-off reflects DCLS-SPMA's aggressive backoff strategy for low delay at the cost of the success rate, whereas MA-SPMA prioritizes transmission reliability and throughput through its utility-based scheduling.

5.2.4. Impact of Node Mobility Speed

To further evaluate the robustness of the proposed MA-SPMA protocol under various mobility conditions, additional simulations are conducted with node mobility speeds of 40 m/s and 60 m/s, while keeping all other simulation parameters unchanged. The results at 20 m/s are already presented in Sections 5.2.1–5.2.3. In this subsection, the three sets of results (20, 40, and 60 m/s) are compared uniformly. The priority service allocation ratio is fixed at 1:1:1, and the per-node total traffic rate is fixed at 2 Mbps. To facilitate a comprehensive comparison across the three priority classes, two unified metrics are introduced: the normalized end-to-end transmission success rate, defined as the average of the three priority success rates divided by their respective QoS requirements (99%, 95%, and 90% for Priorities 0, 1, and 2, respectively), and the normalized end-to-end delay, defined as the average of the three priority delays divided by their respective timeout values (2 ms, 10 ms, and 50 ms for priorities 0, 1, and 2, respectively). All results in this subsection are based on 10 independent runs, and the error bars in Figures 12–14 represent the 95% confidence intervals.

Figure 12 presents the normalized end-to-end transmission success rate of the three protocols under different mobility speeds. As the speed increases from 20 m/s to 60 m/s, the normalized success rates of all three protocols exhibit a declining trend, since higher node mobility leads to more frequent topology changes and increased probabilities of routing failures and packet losses. Notably, MA-SPMA consistently outperforms both DCLS-SPMA and BiLSTM-SPMA across all speed settings. At 20 m/s, the normalized success rates of MA-SPMA, DCLS-SPMA, and BiLSTM-SPMA are 0.329, 0.195, and 0.259, respectively, representing improvements of 68.7% and 27.0%. At 40 m/s, MA-SPMA achieves 0.294, compared with 0.183 for DCLS-SPMA and 0.219 for BiLSTM-SPMA, yielding improvements of 61.0% and 34.5%. At 60 m/s, MA-SPMA still maintains 0.244, while DCLS-SPMA and BiLSTM-SPMA drop to 0.139 and 0.172, corresponding to improvements of 75.5% and 41.9%. More importantly, the performance degradation of MA-SPMA from 20 m/s to 60 m/s is only 25.8%, considerably smaller than that of DCLS-SPMA (28.5%) and BiLSTM-SPMA (33.6%). This demonstrates that the proposed NPTQ mechanism, which maintains per-neighbor queues independently, effectively mitigates the performance loss caused by stale COS information under high mobility—when the COS information of a particular link becomes outdated, the scheduler can still select packets destined for other neighbors, thereby preserving scheduling flexibility.

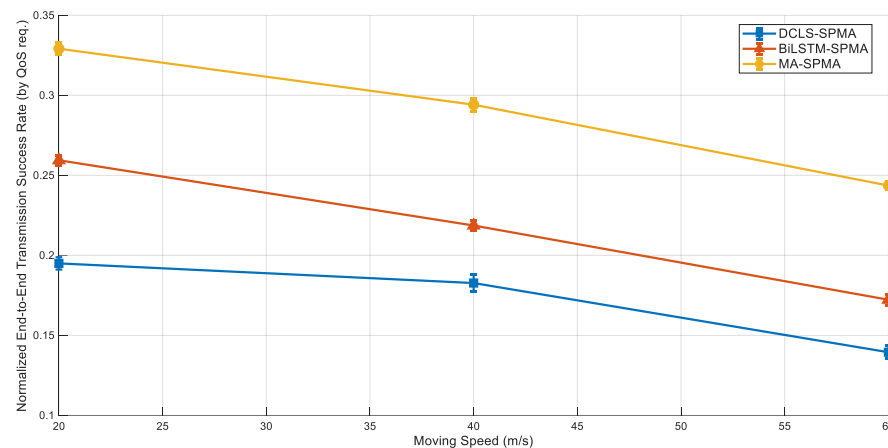


Figure 12. Normalized end-to-end transmission success rate (normalized by QoS requirements) versus node mobility speed. Error bars represent 95% confidence intervals.

Figure 13 shows the network throughput of the three protocols under different mobility speeds. Consistent with the trend of the success rate, the throughput of all protocols decreases as mobility speed increases. MA-SPMA achieves the highest throughput at all speed settings, with values of 3.77, 3.39, and 2.85 Mbps at 20, 40, and 60 m/s, respectively. In comparison, BiLSTM-SPMA achieves 3.30, 2.87, and 2.33 Mbps, while DCLS-SPMA achieves only 1.99, 1.89, and 1.56 Mbps. The throughput degradation of MA-SPMA from 20 m/s to 60 m/s is 24.4%, lower than that of BiLSTM-SPMA (29.4%). It is worth noting that although DCLS-SPMA exhibits the smallest relative degradation (21.6%), its baseline throughput at 20 m/s is already very low (only 1.99 Mbps), leaving limited room for further decline. From the perspective of absolute gain, MA-SPMA maintains a throughput advantage of 1.78 Mbps over DCLS-SPMA at 20 m/s and 1.29 Mbps at 60 m/s and an advantage of 0.48 Mbps over BiLSTM-SPMA at 20 m/s that slightly increases to 0.52 Mbps at 60 m/s. These results further confirm that MA-SPMA preserves its performance superiority even under highly dynamic environments.

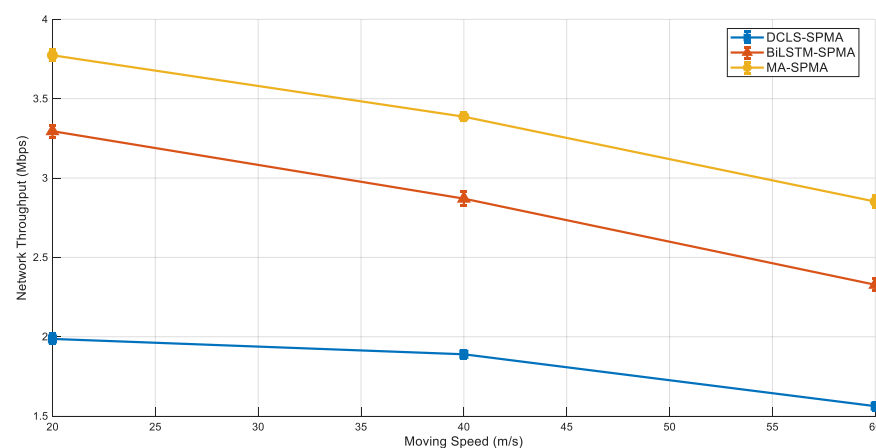


Figure 13. Network throughput versus node mobility speed. Error bars represent 95% confidence intervals.

Figure 14 depicts the normalized end-to-end delay of the three protocols under different mobility speeds. Overall, DCLS-SPMA consistently exhibits the lowest normalized delay, increasing from 0.138 at 20 m/s to 0.405 at 60 m/s. MA-SPMA shows normalized delays of 0.473 at 20 m/s and 0.598 at 60 m/s, while BiLSTM-SPMA exhibits 0.579 at 20 m/s and 0.634 at 60 m/s. It should be noted that the low delay of DCLS-SPMA comes at the cost of a significantly degraded transmission success rate—as shown in Figure 12, DCLS-

SPMA achieves the lowest normalized success rate under all speed conditions. MA-SPMA achieves delays between those of DCLS-SPMA and BiLSTM-SPMA, reflecting its trade-off among multiple performance metrics: by jointly considering delay, priority, and transmission success probability in the utility function, MA-SPMA achieves substantial improvements in transmission reliability and network throughput at the cost of moderate delay, resulting in superior overall performance.

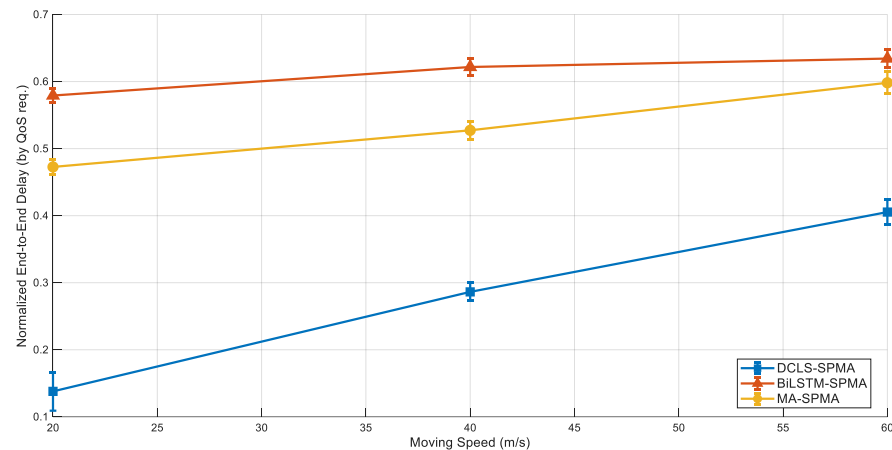


Figure 14. Normalized end-to-end delay (normalized by timeout requirements) versus node mobility speed. Error bars represent 95% confidence intervals.

Table 3 presents the normalized performance metrics and overall scores of the three protocols under different mobility speeds. To enable a fair comparison among the three protocols at the same speed, the three metrics (normalized success rate, throughput, and normalized delay) are further normalized using min–max scaling independently for each speed. The overall score is computed as a weighted sum with weights of 0.5 for the success rate, 0.3 for throughput, and 0.2 for delay (the delay metric is reverse-normalized since lower delay is better). The results show that MA-SPMA achieves the highest overall score across all speed settings (0.848, 0.856, and 0.832 at 20, 40, and 60 m/s, respectively), significantly outperforming BiLSTM-SPMA (0.460, 0.358, and 0.336) and DCLS-SPMA (0.200 at all speeds). DCLS-SPMA achieves the best normalized delay performance due to its aggressive backoff strategy, but this comes at the cost of a substantially lower success rate and throughput, resulting in the lowest overall score. These quantitative results confirm that MA-SPMA provides the best comprehensive performance under various mobility conditions.

Table 3. Normalized performance metrics and overall scores of the three protocols under different mobility speeds.

Moving Speed (m/s)	Protocol	Rel. Success Rate	Rel. Throughput	Rel. Delay	Overall Score
20	DCLS-SPMA	0.000 ± 0.029	0.000 ± 0.017	1.000 ± 0.065	0.200
	BiLSTM-SPMA	0.480 ± 0.022	0.732 ± 0.021	0.000 ± 0.025	0.460
	MA-SPMA	1.000 ± 0.027	1.000 ± 0.019	0.241 ± 0.024	0.848
40	DCLS-SPMA	0.000 ± 0.050	0.000 ± 0.017	1.000 ± 0.040	0.200
	BiLSTM-SPMA	0.323 ± 0.026	0.655 ± 0.029	0.000 ± 0.037	0.358
	MA-SPMA	1.000 ± 0.036	1.000 ± 0.018	0.282 ± 0.040	0.856
60	DCLS-SPMA	0.000 ± 0.038	0.000 ± 0.020	1.000 ± 0.082	0.200
	BiLSTM-SPMA	0.315 ± 0.032	0.593 ± 0.030	0.000 ± 0.058	0.336
	MA-SPMA	1.000 ± 0.026	1.000 ± 0.030	0.158 ± 0.072	0.832

Note: Values are presented as mean ± 95% confidence interval. Rel. success rate and rel. throughput are forward indicators (larger is better); rel. delay is a reverse indicator (smaller is better, normalized).

as larger value indicates better performance). The best overall score in each speed group is highlighted in **bold**. Normalization is performed independently for each speed using min–max scaling. All results are based on 10 independent runs.

In summary, the simulation results in Section 5.2.4 demonstrate that MA-SPMA exhibits stronger resistance to node mobility compared with DCLS-SPMA and BiLSTM-SPMA. The NPTQ mechanism provides natural tolerance to transient link outages and COS staleness, while the PUDD mechanism enables adaptive scheduling decisions across a wide range of mobility speeds, thereby maintaining high transmission reliability and throughput. These results collectively validate that MA-SPMA is well-suited for FANET scenarios where UAV nodes move at various high speeds.

6. Discussion

The SPMA protocol provides a preset high transmission success rate through threshold-based traffic control and millisecond-level end-to-end delay through ALOHA-like random access, making it especially suitable for delay-sensitive and multi-task airborne and UAV communication scenarios. Existing studies mostly focus on the modification and optimization of specific parameters and methods such as the priority transmission threshold, random backoff window, and channel load measurement. With the increasing popularity of FANETs and UAV swarms, the structural and systematic defects of the SPMA protocol that are incompatible with multi-hop networks are gradually exposed, indicating the necessity of redesigning the overall framework and mechanism.

The main contributions of this paper can be summarized as four points:

1. Two types of structural defects of traditional SPMA in multi-hop networks are revealed: first, single-dimensional packet storage only by priority cannot utilize channel load differences between different receiving nodes to obtain better transmission opportunities; second, FIFO queueing leads to delayed processing of multi-hop forwarding packets due to late arrival time, easy timeout discards, and network bottlenecks.
2. The Neighbor-Priority Two-Dimensional Queueing (NPTQ) mechanism is proposed: extending the traditional single-dimensional priority queue to a two-dimensional queue structure of “grouped by neighbor, classified by priority” enables nodes to perceive channel states of different next hops in parallel and fully exploit transmission opportunities in multi-hop networks.
3. The Priority-Utility Dual-round Decision (PUDD) mechanism is designed: in the first round, eligible candidate queues are selected in parallel; in the second round, global optimization is performed based on the utility function integrating delay, priority, the transmission success rate, and remaining hops, improving overall network throughput while guaranteeing high-priority QoS.
4. Comprehensive performance advantages of MA-SPMA are verified by simulation: a complete implementation process of MA-SPMA is constructed, and complexity analysis is completed to prove controllable overhead; simulation results in typical multi-hop FANET scenarios show that the proposed protocol significantly improves the transmission success rate and throughput compared with DCLS-SPMA and BiLSTM-SPMA, especially in multi-hop service scenarios.

Simulation results show that the proposed method can fully utilize better transmission opportunities brought by real-time changes in multi-hop network topology and node mobility, with obvious comprehensive advantages in the transmission success rate, network throughput, and end-to-end delay. For example, when the node mobility speed is 20 m/s and the priority service allocation ratio is 1:1:1, compared with DCLS-SPMA, MA-

SPMA improves the transmission success rates of the three services by up to 38.82, 17.57, and 16.59 percentage points, respectively, and network throughput by up to 170.05%. Compared with BiLSTM-SPMA, MA-SPMA improves the transmission success rate of priority 2 by up to 26.62 percentage points and network throughput by up to 37.44%. These results fully indicate that there is still huge room for improvement and optimization of the SPMA protocol for mobile multi-hop network scenarios. Furthermore, as demonstrated in Section 5.2.4, the performance superiority of MA-SPMA is sustained across a wide range of mobility speeds (20, 40, and 60 m/s), confirming its robust adaptability to highly dynamic FANET environments.

While the above simulation results validate the effectiveness of MA-SPMA, a deeper discussion is necessary to fully position the proposed protocol within the broader research landscape and to examine its limitations and practical considerations. To this end, we first compare MA-SPMA with heuristic-based approaches and discuss its robustness and potential for extension to other vehicular network scenarios. We then explore the potential of heuristic methods for further enhancing MA-SPMA, followed by an analysis of its limitations and design trade-offs. Finally, we discuss security implications, compare them with MARL-based approaches, analyze control overhead and COS freshness, and examine the real-time feasibility of the proposed algorithm.

Comparison with heuristic-based approaches and robustness discussion. We note that recent works have demonstrated the effectiveness of heuristic and metaheuristic methods in enhancing MAC or routing protocol performance in vehicular networks [28,29]. In particular, in [28], Tripti et al. proposed ACO-CMAC, which applies ant colony optimization (ACO) to cluster head selection in VANETs and combines it with a priority-driven contention window adjustment mechanism based on IEEE 802.11p EDCA. Their results show significant improvements in terms of cluster stability, the packet delivery ratio, and end-to-end delay compared with the IEEE 802.11p standard.

We compare ACO-CMAC with our MA-SPMA from three perspectives. First, regarding the target network, ACO-CMAC focuses on VANETs, where the primary challenge is maintaining stable cluster structures under high node mobility, whereas MA-SPMA targets FANETs and focuses on overcoming the queueing and scheduling deficiencies of the SPMA protocol in multi-hop topologies. Second, regarding the underlying protocol, ACO-CMAC operates on the IEEE 802.11p EDCA framework, while MA-SPMA is built upon the SPMA protocol, which employs threshold-based traffic admission control to provide deterministic QoS guarantees. Third, regarding the decision time scale, ACO-CMAC relies on iterative optimization with a relatively long convergence time, making it suitable for offline or coarse-grained decisions, whereas MA-SPMA performs online slot-by-slot scheduling with a 10 μ s time-slot granularity. These differences reflect complementary design philosophies rather than superiority of one approach over the other.

Regarding robustness and the potential for extension to VANETs, we evaluated MA-SPMA under various mobility speeds (20, 40, and 60 m/s), as presented in Section 5.2.4. The results show that MA-SPMA demonstrates superior robustness against topology dynamics compared with the two benchmark protocols. In addition, the NPTQ mechanism, which maintains per-neighbor queues independently, provides natural tolerance to transient link outages or load fluctuations on any single link. Regarding the potential for VANETs, although MA-SPMA is currently designed upon the SPMA protocol, its core ideas—neighbor-grouped queueing and utility-based scheduling—can be migrated to other contention-based MAC frameworks. To apply MA-SPMA in VANETs under the IEEE 802.11p/EDCA framework, the SPMA threshold control would need to be replaced with EDCA contention window adjustment, while the per-neighbor queue structure could still effectively mitigate the link-state heterogeneity caused by high node mobility in VANETs. This direction merits future investigation.

Potential of heuristic methods for MA-SPMA enhancement. Beyond the above comparison, we further discuss the potential of heuristic methods for improving the proposed technique. First, heuristic methods are well-suited for offline combinatorial optimization problems. Within the MA-SPMA framework, ACO, GA, or PSO could be employed during network initialization to determine near-optimal configurations of key parameters, including priority transmission thresholds, base backoff window sizes, and the weighting factors in the utility function. These parameters, once optimized, remain valid throughout a mission period without affecting online decision latency. Second, when the network undergoes significant changes due to node join/leave or large-scale maneuvers, heuristic-based lightweight reconfiguration can be triggered to adapt MA-SPMA parameters to the new environment. Third, we acknowledge the practical constraint that directly incorporating iterative heuristic methods into the slot-level decision loop of SPMA is challenging, as ACO typically requires tens to hundreds of iterations to converge. Thus, a more feasible integration path is the hierarchical architecture: offline heuristic optimization for parameter configuration followed by online MA-SPMA execution for real-time scheduling. This direction is one of our primary focuses for future research.

Limitations and design trade-offs. We also acknowledge several limitations of MA-SPMA. Compared with traditional SPMA, MA-SPMA requires maintaining $N(i) \times M$ queues per node and computing utility values for candidate packets, which inevitably increases computational and memory overhead. Although the complexity remains $O(N(i))$, this may become a bottleneck in scenarios with extremely high node density. Nevertheless, since the complexity depends only on the local neighbor count rather than the total network size, MA-SPMA remains suitable for resource-constrained UAV platforms. In addition, simulation results show that MA-SPMA incurs a slight increase in end-to-end delay for single-hop high-priority traffic compared with DCLS-SPMA, which prioritizes the “most urgent” data. This is because the MA-SPMA scheduler jointly considers delay, priority, and transmission success probability in its utility function, representing a design trade-off that improves overall network throughput and multi-hop fairness at the cost of acceptable delay increases for single-hop high-priority services.

Security implications. Although MA-SPMA is not a security mechanism by itself, its design features may have positive security implications. First, the NPTQ mechanism, which maintains per-neighbor queues independently, can isolate attack traffic: even if a malicious neighbor node is compromised and continuously injects malicious traffic, the impact is confined to the corresponding neighbor group rather than causing network-wide congestion. Second, since MA-SPMA scheduling is based on real-time channel state of the next-hop neighbor, it can naturally avoid forwarding packets to jammed or congested nodes, providing certain resilience against denial-of-service (DoS) attacks at the physical and link layers. Third, the priority mechanism of MA-SPMA can ensure that critical security signaling (e.g., key updates, authentication messages) is assigned the highest priority and expedited via the utility function, thereby securing the network foundation.

However, we acknowledge potential security risks: MA-SPMA relies on periodic HELLO messages to exchange neighbor COS information, which may be vulnerable to HELLO spoofing attacks or COS value tampering—a malicious node could falsely inflate its channel occupancy to preempt transmission resources. To address this, lightweight hash-based verification could be added to HELLO messages in future work, requiring no complex encryption and fitting within UAV computational constraints. This is one of our key directions for future security enhancements.

Comparison with MARL-based approaches. We further compare MA-SPMA with MARL-based MAC protocol learning approaches, as exemplified by [27]. Although both approaches aim to improve MAC performance, they differ fundamentally in the following aspects. First, the problem definitions differ: existing MARL methods aim to let agents

learn a complete MAC protocol from scratch, whereas our work performs targeted optimization of specific structural deficiencies of the existing SPMA protocol in multi-hop networks. Our design is interpretable and analyzable, with performance bounds guaranteed through theoretical analysis. Second, feasibility differs: MARL methods, particularly the CTDE framework, typically require extensive information exchange and computational resources during training and deployment, which may face serious feasibility challenges in resource-constrained, highly dynamic FANET environments. In contrast, MA-SPMA is a lightweight, fully distributed protocol with a computational complexity of only $O(N(i))$, better suited for practical UAV platforms. Third, the core objectives differ: our goal is to solve the queue management and scheduling problems of SPMA in multi-hop environments, a specific but critical sub-problem at the MAC layer. Unlike MARL approaches that aim to discover entirely new protocols, our work activates and enhances the potential of an already widely deployed protocol (SPMA) through structural innovation.

Control overhead and impact of node mobility. We provide further analysis on control overhead and COS freshness. First, regarding overhead, disseminating COS via HELLO messages is a standard operation for SPMA protocols in multi-hop networks, and our algorithm follows this approach. Since COS requires only 1 byte, while the entire HELLO packet is 100 bytes, the COS overhead is only 1%. Routing protocols such as OLSR are essential for multi-hop networks and are not specific to SPMA; our algorithm does not introduce any additional fields to routing protocols, thus incurring no extra overhead from OLSR.

Second, COS estimation error is indeed affected by node mobility. As presented in Section 5.2.4, we compared the performance of the three protocols at 20 m/s, 40 m/s, and 60 m/s. The results show that MA-SPMA consistently outperforms DCLS-SPMA and BiLSTM-SPMA in terms of the normalized transmission success rate, throughput, and overall score across all speed settings. The underlying reasons are summarized as follows.

High mobility may cause transient link outages between a node and some of its neighbors. As long as the node is not disconnected from all neighbors, the NPTQ mechanism of MA-SPMA maintains per-neighbor queues independently. In the first-round decision, the scheduler can filter out the currently disconnected neighbors and select candidate queues from the remaining connected ones. In this case, transmission is not interrupted, and opportunistic scheduling gains are largely preserved. In contrast, existing protocols, including DCLS-SPMA and BiLSTM-SPMA, can only select the head-of-line packet from a single priority queue. When the link to the intended next-hop receiver is broken, the node must suspend transmission until the link recovers, or until the head-of-line packet times out and a new head-of-line packet with an intact next-hop link becomes available. During this period, multiple time slots are wasted. This is the primary reason why MA-SPMA outperforms existing algorithms under high mobility.

If high mobility causes a node to lose connectivity to all neighbors, MA-SPMA, like all other protocols, cannot transmit, and no performance gain is achieved.

In addition to link outages, high mobility may also cause HELLO packets carrying COS information to be delayed or dropped, preventing timely COS updates and forcing the node to rely on stale COS information. This is another important factor contributing to the performance degradation of all three protocols as mobility speed increases, as observed in the supplementary simulation results. For example, when the true COS value is 0.09 and the estimated value is 0.085, the estimation error is small. In this case, all protocols can still make correct scheduling decisions because the highest-priority threshold is 0.1 and the second-highest threshold is 0.08, so only the highest-priority traffic is permitted to transmit. However, when the estimation error is large—for example, when the true COS is 0.09 but the estimated value is 0.075—all protocols will make erroneous decisions, as both the highest- and second-highest-priority traffic are incorrectly deemed eligible for

transmission, leading to degraded performance. In the presence of such errors, MA-SPMA mitigates the impact through its opportunistic scheduling mechanism, whereas the benchmark protocols lack such resilience and are more severely affected.

In summary, high node mobility increases both the probability of link outages and the magnitude of COS estimation errors. The proposed MA-SPMA protocol mitigates these effects to a certain extent through opportunistic scheduling but cannot completely eliminate them. Existing protocols, however, lack such mitigation mechanisms and are fully exposed to these impairments. This explains why, although all protocols experience performance degradation at higher speeds, MA-SPMA consistently maintains superior performance.

Real-time feasibility analysis. We further analyze the real-time feasibility of MA-SPMA given the stringent 10 μ s time-slot duration. In the worst-case scenario of our simulation setup (17 nodes, three priorities, and a maximum queue length of 100 packets), the upper bound of candidate packets entering the second-round utility calculation is 5100. However, this theoretical upper bound is rarely reached in practical multi-hop SPMA networks due to four factors: (1) the first-round priority threshold screening typically filters out 70–90% of queues; (2) the queue non-empty probability further reduces the candidate set; (3) the average number of neighbors per node is limited (≤ 6 in our simulation topology); and (4) a computational cap can be imposed as an engineering safeguard. In our simulations, the average number of candidate packets per slot is approximately 30. With LUT-based optimization for $P_s(pkt)$ calculation, the per-slot scheduling decision requires only about 150 floating-point operations and can be completed within 0.3–0.6 μ s on an ARM Cortex-A53 processor (1.2 GHz). Given that scheduling decisions can be parallelized with other time-critical processing tasks (e.g., reception demodulation/decoding, frame encapsulation, and RF switching), the proposed algorithm imposes no bottleneck on real-time system performance.

7. Conclusions

Aiming at the structural defects of the traditional SPMA protocol in multi-hop FANETs, this paper proposes a multi-hop adaptive Statistical Priority-Based Multiple Access protocol (MA-SPMA) suitable for dynamic multi-hop scenarios. The protocol reconstructs traditional SPMA from two aspects: queue storage architecture and the transmission decision mechanism. The core innovations include two mechanisms, Neighbor-Priority Two-Dimensional Queueing (NPTQ) and Priority-Utility Dual-round Decision (PUDD), which effectively solve the problems of traditional SPMA such as single-dimensional queueing only by priority, unreasonable FIFO scheduling, easy timeout discarding of multi-hop forwarding packets, and insufficient utilization of channel opportunities.

Theoretical analysis shows that the time and space complexity of MA-SPMA are linearly related to the number of neighbor nodes, with controllable computing and storage overhead, enabling distributed real-time operation on resource-constrained UAV platforms. Simulation results show that compared with DCLS-SPMA and BiLSTM-SPMA, the proposed protocol significantly improves the end-to-end transmission success rate and network throughput under two typical service rate ratios, with more prominent advantages in scenarios having a higher proportion of multi-hop services. Although there is a slight sacrifice in the end-to-end delay of single-hop high-priority services, it overall achieves a significant improvement in transmission reliability and network capacity at the cost of acceptable delay, with optimal comprehensive performance.

This work verifies the feasibility and effectiveness of reconstructing the SPMA protocol in terms of the queue architecture and scheduling mechanism to adapt to multi-hop networks, providing new insight into MAC layer protocol design for high-speed mobile multi-hop communication scenarios such as UAV swarms and FANETs. Future work can

further optimize the nonlinear modeling of utility functions, improve channel load estimation accuracy, and promote the practical application of the protocol in engineering systems.

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Abbreviations

Abbreviation	Full Form
ACO	Ant Colony Optimization
BiLSTM	Bidirectional Long Short-Term Memory
COS	Channel Occupancy Statistics
CTDE	Centralized Training with Decentralized Execution
DCLS	Distributed Channel Load Sensing
DoS	Denial-of-Service
EDCA	Enhanced Distributed Channel Access
FANETs	Flying Ad Hoc Networks
FIFO	First-In-First-Out
MAC	Medium Access Control
MA-SPMA	Multi-hop Adaptive SPMA
MAPPO	Multi-Agent Proximal Policy Optimization
MARL	Multi-Agent Reinforcement Learning
MPR	Multipoint Relay
NPTQ	Neighbor-Priority Two-Dimensional Queueing
OLSR	Optimized Link State Routing
PUDD	Priority-Utility Dual-round Decision
QoS	Quality of Service
RPGM	Reference Point Group Mobility
SPMA	Statistical Priority-Based Multiple Access
TC	Topology Control
UAV	Unmanned Aerial Vehicle
VANETs	Vehicular Ad Hoc Networks

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