A Load Statistics-Based Frequency-Hopping Multiple Access Protocol with QoS Guarantee

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Abstract. In order to satisfy the needs of flexible and invulnerability in aeronautical Ad hoc networks, statistic priority-based multiple access (SPMA) was applied to the tactical target network technology (TTNT) system, which is the latest generation of US military tactical data links. SPMA can provide different access rates and channel resources for different priority traffic. However, if the traffic is busy, low-priority traffic is likely to result in the problem of starvation. This paper proposes a load statistic-based frequency hopping multiple access protocol (LSMA) to solve the starvation problem of low-priority traffic in SPMA and also ensure the network throughput and packet loss rate. The protocol first schedules multiple priority queues. Then according to the statistical results of the physical layer network load, a rate adaption algorithm is designed to control the sending rate of each node in the network. Simulation results show that LSMA can not only solve the starvation problem of low-priority traffic in SPMA, but also provide weighted throughput for every priority traffic. And the network load under this protocol is more stable. When the throughput under high traffic volume in LSMA is same to that in SPMA, packet loss rate dropped from 27% to 10%.

Keywords: Multiple access · QoS · SPMA · Aeronautical ad hoc networks

1 Introduction

The Mobile Ad Hoc Network (MANET) [3,9] is a network in which nodes can communicate and relay with each other without the support of fixed facilities like base stations. Every node in the MANET has the same function. They can transmit, receive and even relay the wireless signal, so the networking mode is flexible. When the network topology has been destroyed, it can form a new network topology and recover communication quickly.

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The MANET used in aeronautical communication is called Aeronautical Ad hoc Networks (AANET) [10]. In AANET, the network nodes are moving at a high speed, and the network topology changes continuously with an unstable channel, which greatly affects the quality of communication. As a plenty of new traffic has springing up, the quality of service (QoS) required by different services is various. Therefore, how to realize fast and efficient communication in AANET and ensure the QoS of the service, the design of multiple access control (MAC) protocol is very important.

In order to establish an efficient and reliable aerospace communication system with strong resistance to damage, the Collins company of the United States has proposed a patented technology statistic priority-based multiple access (SPMA) [4]. It is the multiple access protocol used by the US next generation Tactical Targeting Network Technology (TTNT) [5]. The TTNT data link uses frequency-hopping technology at physical layer to achieve virtual full-duplex communication [8,13]. Figure 1 shows a schematic of the SPMA protocol. In the SPMA protocol, each priority traffic occupies one queue for transmission independently, and Each priority queue sets a threshold in advance. And the physical layer counts the load status of the network and obtains a network load statistic. When there are data packets in the queue needing be sent, it will compare the current network load statistics and the threshold of this queue first. When the network load statistic is lower than the queues's threshold, the data packet is allowed to be transmit. Otherwise, backoff is required. After the backoff, the queue's threshold and the new network load statistics in the current period are compared again.

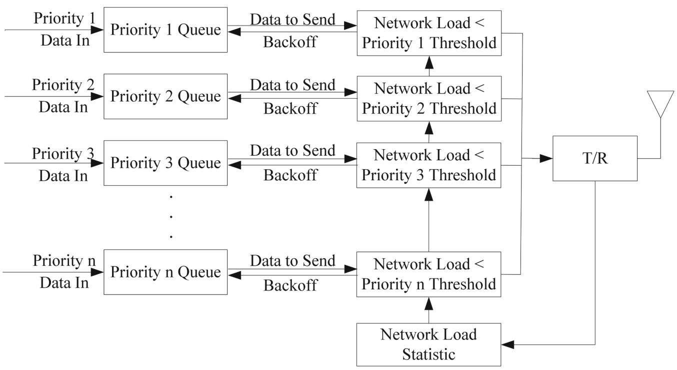

Fig. 1. SPMA protocol diagram

In [2,7], a multichannel Slotted-ALOHA protocol is proposed. The channel statistics are used to achieve feedback-free multiple access. The protocol flow is consistent with SPMA. The paper [11,12] propose a specific access control method based on the channel statistics of SPMA instead of the feedback mechanism. A channel collision model is established, and a method of setting a priority threshold is given. These articles all use SPMA's channel statistics instead of feedback mechanisms. The higher the service prioritiy is, the higher the threshold sets and the greater the possibility of access to the channel is. To ensure high timeliness of high priority traffic, if there are high-priority packets arriving while the low-priority queue is in a backoff state, canceling the backoff process. Then comparing the network load statistics with the threshold of the high-priority queue to decide if the high-priority packets can be transmit. This type of access guarantees high timeliness of high-priority traffic. And because of the higher threshold, high-priority traffic can occupy higher channel bandwidth. However, when the network load is high, the queues with threshold lower than the network load statistic cannot send packets. Because the backoff process of the low-priority queue can be interrupted the high-priority queue, if there are too many data packets in the high-priority queue (the high-priority queue can always send the data packet), the low-priority queue cannot send any data packet. Both of these conditions can cause the starvation problem in the low-priority queue (data packets cannot be sent).

Reference [6] proposed a priority weighted rate control algorithm in aeronautical Ad hoc networks. This article uses the classic weighted fair queue scheduling algorithm (WFQ) [1] to schedule multiple queues, and still sets a threshold for each priority queue based on SPMA. When the network load is higher than the threshold, it cannot send packets. This method solves the problem that the low-priority traffic cannot be sent if the low-priority traffic is saturated. However, when the network load is high, the low-priority traffic still cannot be sent. Then, this article will design a protocol (LSMA), which can solve the problems above.

This paper raises a load statistic-based frequency hopping multiple access protocol (LSMA) to ensure service QoS. The protocol allocates different bandwidths by scheduling multiple priority traffic first. Secondly, it calculates the load status of the network from the physical layer, and designs a load statistic-based rate control algorithm to control the network load and improve throughput.

The rest of this paper can be divided into the following sections: The Sect. 2 will introduce the system model of this article. The Sect. 3 will describe the protocol design and algorithm implementation of the LSMA specifically. It will also show how to schedule multiple priority traffic, calculate load statistic, and control the node's sending rate. In Sect. 4, the simulation scenario is designed. The simulation of LSMA and SPMA is compared using the OPNET simulation tool, and analyzing the system performance based on the simulation results. In the last Sect. 5, this paper will be summarized.

2 System Model

To ensure the QoS of different priority traffic and solve the starvation problem of low-priority traffic, the system model is given as follows:

In a fully connected network, N nodes are distributed randomly and every node has the same functionality. Each node can generate n different priority traffic. Each priority traffic is maintained by one queue, in which the data packets use first input first output (FIFO) system. The physical layer uses frequency hopping technology. The data packet is split into multiple pulses first, and sent according to the frequency-hopping pattern. And each node works in full-duplex mode, which can transmit data in 1 channel and receive data with 4 channels at the same time.

Network load statistics follow the method of SPMA. A packet is split into pulses before transmitting, and the corresponding frequency point is selected for each pulse according to the designed frequency hopping pattern. Therefore, different pulses can occupy different channels for sending or receiving simultaneously. Based on this, the SPMA protocol achieves 1 channel for transmission and 4 channels for reception. It can improve the throughput of the network effectively.

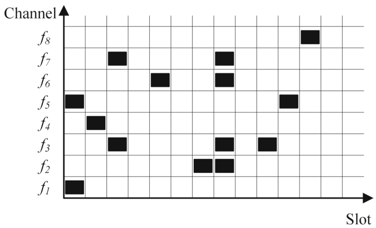

Fig. 2. System model

As shown in Fig. 2, when there are several nodes requiring to send packets in the network, each node will select one frequency for each pulse to transmit. Each frequency occupies one channel, and multiple channels are allowed to be occupied at the same time slot. When different nodes send the same frequency pulse in the same time slot, they will occupy the same channel, which causes collision. Setting the load statistics period is T, and counting the number of pulses sent by a node in the T period, the pulse sending rate μ_s of the node can be obtained. In the same way, we can get the rate of pulse reception μ_r.

3 Protocol Design and Algorithm Implementation

The core framework of the LSMA is shown in Fig. 3. This protocol includes multiple priority queues, service scheduler, rate control algorithm, network load statistic, and transmit and receive antennas. In order to solve the low-priority starvation problem, the data packets of multiple priority queues are scheduled first to ensure that every queue's packets have the opportunity to be scheduled. With the scheduling algorithm, every time the data packet is transmitted considering only one packet, instead of multiple queue packets. The priority threshold set by SPMA is not applicable. According to the network load statistic of physical layer, we can obtain the sending rate of the packet by the rate control algorithm to control the network load. After that backoff and send the data packet.

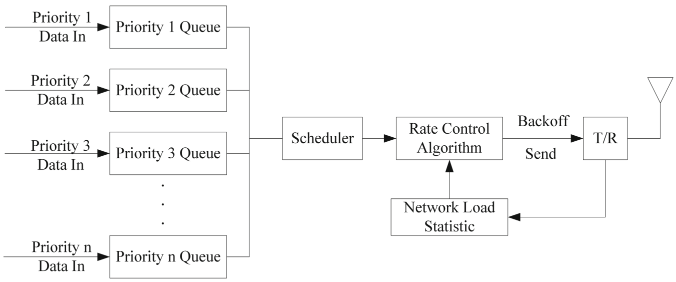

Fig. 3. LSMA protocol core framework

3.1 Multi-queue Scheduling Algorithm

The multi-queue scheduling algorithm is shown in Fig. 4. This algorithm schedules queues based on WFQ and considers non-saturated services. First, set a sequence number s for each packet in the queue, and the weight of queue i is w_i. Assuming that the sequence number of the header packet in queue i is s_i, then the sequence numbers of other packets in queue i are increased w_i in order, which is $\{s_i + w_i, s_i + 2w_i, \cdots\}$.

When scheduling the packets, select the packet with the smallest sequence number in the range of all the queues. This packet also has the smallest sequence number in the header of all the queue. This sequence number is denoted as S, and $S = \min_{i=0}^{n} s_i$. If there are several queues with the same sequence number, they are sent according to the priority.

Assuming that the initial value of all queue serial numbers is 0. If there is a new packet entering the non-empty queue i, the sequence number of the data packet is added the weight w_i on the base of the queue tail sequence number s_i^{tail}. And it is $s_i^{tail} + w_i$. If there is a new data packet entering the empty queue i, it is assumed that the sequence number of this packet is added weight w_i based on the sequence number of the last packet sent from the queue. We can get the sequence number of this packet is $s_i^{'} + w_i$. However, because the packet with the sequence number $s_i^{'}$ has been sent, $s_i^{'} \leq S$, it is likely that $s_i^{'} + w_i$ will be smaller than the sequence number of packets that have higher priority than i and have not yet been sent. It will cause that the packets entered the queue with higher priority earlier may be sent even later than the ones that have just entered the lower priority queue. This is not fair.

In order to prevent that when non-saturated service packets enter the queue the sequence number is too small, which will cause unfairness for existing packets in the higher-priority queue. If there is a new packet entering the empty queue i, the packet sequence number will be added the weight w_i on the base of S, which is, $S + w_i$. For example, the sequence number of new packet in queue 2 is $s_2 = S + w_2$ in the Fig. 4.

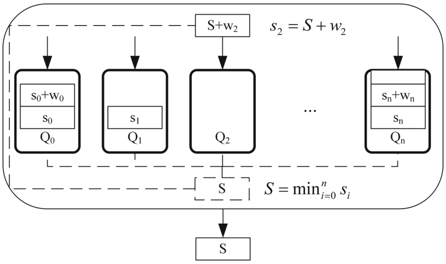

Fig. 4. Multi-queue scheduling algorithm

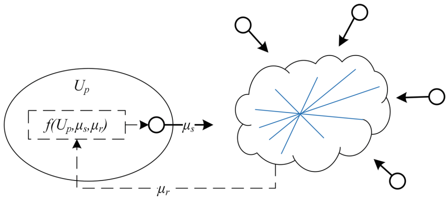

Fig. 5. Rate control algorithm

3.2 Rate Control Algorithm

The rate control algorithm is designed based on the node pulse sending rate μ_s and the receiving rate μ_r counted by physical layer. The sum of the pulse sending rate and the receiving rate $\mu_s + \mu_r$ constitutes the total network load. To control the packets loss rate and throughput in the network, we can limit the total load or the number of pulses.

First, let U_p indicate the desired network load threshold. Secondly, physical layer calculates μ_s and μ_r once per rate update period T. Then, according to the rate update function $f(U_p, \mu_s, \mu_r)$, we can calculate the allowed rate $\mu_s^{'}$ of the node as the next period sending rate. Update the sending rate every T periods. Finally, after the packets backoff time is calculated according to the sending rate $\mu_s^{'}$, backoffing and sending it. The rate update formula is as follows:

$$\mu_s^{'} = \begin{cases} \mu_s + \Delta, & U_p - \mu_r - \mu_s > \Delta \\ \mu_s - \Delta, & \mu_r + \mu_s - U_p > \Delta \&\& \mu_s - \Delta > 0 \\ \mu_s, & other \end{cases} \quad (1)$$

$$\Delta = \begin{cases} \Delta_0, & |U_P - \mu_r - \mu_s| \le B \\ 2\Delta, & U_p - \mu_r - \mu_s > \Delta or \begin{pmatrix} \mu_r + \mu_s - U_p > \Delta \\ \&\& \mu_s - \Delta > 0 \end{pmatrix} \\ \Delta/2, & other \end{cases} \quad (2)$$

Equation (1) calculates the service sending rate $\mu_s^{'}$ for the next period, where Δ is the rate change increment and Δ_0 is the initial value of Δ. Δ varies according to Eq. (2), where B is the sending rate error tolerance.

For formula (1), when U_p is greater than the total network load $\mu_s + \mu_r$ and the difference exceeds Δ, the sending rate of the node need to be increased. Similarly, when U_p is less than the total network load $\mu_s + \mu_r$, the sending rate needs to be reduced. Since the sending rate cannot be negative, $\mu_s - \Delta > 0$ must be guaranteed. In other cases keeping the sending rate unchanged.

For formula (2), when the difference of $\mu_s + \mu_r$ and U_p are not more than the error tolerance B, it is considered that the network load at this time is in a stable state. Keeping the transmission rate unchanged while restoring Δ to the initial value Δ_0. When the total network load and U_p differ greatly and the sending rate needs to be adjusted, increasing Δ to double to enable the network load to be adjusted to U_p quickly. In other cases, reducing Δ to half, including when the difference of i$\mu_s + \mu_r$ and U_p are greater than the tolerance B but lower than Δ, and when the total network load is too large but $\mu_s - \Delta > 0$. In the both cases, the transmission rate cannot be adjusted directly, we need reduce Δ to make sure the sending rate can be altered.

4 Performance Evaluation

To compare the performance of SPMA and the protocol designed in this paper, we need to simulate the two protocols. SPMA is simulated first. Building a network with size of 10 km × 10 km, and placing 6 identical nodes. Each node maintains 4 priority queues (priority order: Queue 1 > Queue 2 > Queue 3 > Queue 4). The service of each queue is Poisson's arrival service, and the size of the transmitted data packet is 1024 bits. Changing the size of the traffic and observing the changes of network throughput and packet loss rate.

The traffic rate for each queue is set to {100, 200, 500, 1000, 2000, 3000} packets per second. The parameter settings of SPMA protocol are shown in Table 1, including the thresholds of 4 priority queues and the load statistics period T.

Table 1. Simulation parameters of SPMA

Paramter name	Values
T	0.5s
The threshold of queue 1	80000(pulses/s)
The threshold of queue 2	60000(pulses/s)
The threshold of queue 3	40000(pulses/s)
The threshold of queue 4	20000(pulses/s)

Figure 6 illustrates how the SPMA protocol network load changes with service traffic. It can be seen that as the increase of traffic, the total pulse sending rate in the network increases gradually, while the total pulse receiving rate increases first before stabilizing at about 68,000. Comparing the service delivery status of the 4 priority queues, the service is more saturation, the proportion of queue 1 in the sent packets becomes higher. And the queue with lower priority appears starvation problem earlier, until only the packets of queue 1 can be sent in the end.

In order to make the LSMA protocol compared with the SPMA protocol at the same throughput, we set the parameter U_p according to the SPMA simulation result. When the SPMA throughput is maximum, the pulse receiving rate is approximately 68000 pulses per second. Considering that the network always

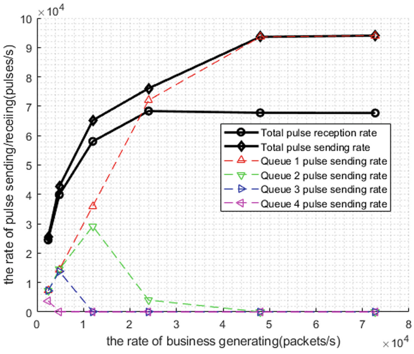

Fig. 6. Network load curve of SPMA

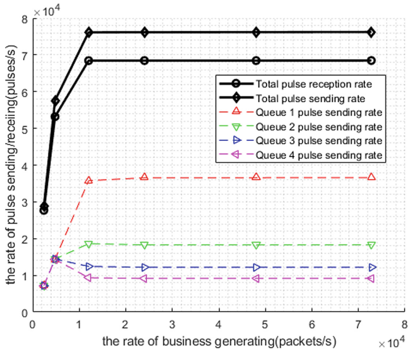

Fig. 7. Network load curve of LSMA

has packets loss, we set the value of U_p to 72000 pulses per second [1]. Other parameter settings are shown in Table 2. The traffic rate setting for each queue is unchanged.

Table 2. Simulation parameters of LSMA

Paramter name	Values
T	0.5s
U_p	72000(pulses/s)
Δ	$0.25U_p/N$
B	60
w_1	1
w_2	2
w_3	3
w_4	4

Figure 7 show the changes of network load in LSMA. With the increase of traffic, the total pulse transmission rate and pulse reception rate in the network increase first, and then remain stable. It means that the LSMA's rate control algorithm can control the network load effectively, so that the network's total pulse sending rate is controlled in the vicinity of U_p. When the network load reaches the maximum, the service sending rate of the four queues becomes a certain ratio (12:6:4:3), which is inversely proportional to the weight (1:2:3:4). By setting the weight of the queue to allocate a different proportion of bandwidth for the queue, the resulting proportional throughput is called the weighted throughput.

[1] Testing several times, selecting the sending rate when the receiving rate is same to that in SPMA. We get the value is 72000. The test process is not given in this paper.

The changes of throughput and packet loss rate in SPMA and LSMA are illustrated in Figs. 8 and 9 respectively. Although the throughput of both increases first and then remains stable, the LSMA reaches its maximum value when the traffic is 12,000 packets per second. While the SPMA reaches its maximum value when the traffic is 24000 packets per second. And when the traffic is lower than this traffic, the throughput of SPMA is always lower than that of LSMA, but they packet loss rates are similar. It indicating that the sending rate of the SPMA protocol packet is lower, which causes a waste of network resources. When the traffic exceeds 24,000 packets per second, the packet loss rate of SPMA reaches about 27%, which is significantly higher than that of LSMA (only 10%).

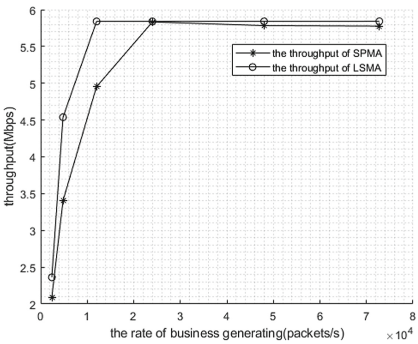

Fig. 8. Throughput comparison

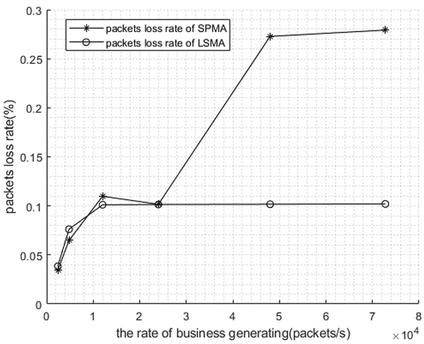

Fig. 9. Loss rate comparison

Comparing SPMA and LSMA comprehensively, LSMA's multi-queue scheduling algorithm assigns weighted throughput to each priority queue. It satisfies the bandwidth requirements for different priority traffic. The network has a better performance in the LSMA protocol. Its packet loss rate is lower, when the throughput is the same.

5 Conclusion

In AANET, for the purpose of solving the low-priority starvation problem of SPMA and meet the QoS requirements of different priority traffic, this paper proposes a load statistic-based frequency hopping multiple access protocol LSMA.

LSMA allocates different bandwidths for different priority traffic by multi-queue scheduling algorithm, and obtains weighted throughput. Secondly, LSMA designs a rate adaptive adjustment algorithm in conjunction with the layer network load statistic to keep the network load steadily. Only using one parameter U_p to control the sending of packets, and U_p indicates the size of the network load approximately. Comparing LSMA with SPMA by simulation, LSMA not only solves starvation of low-priority queues in SPMA, but also can control network packet loss rate to a lower level and guarantee service QoS better.

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References

1. Bensaou, B., Wang, Y., Chi, C.K.: Fair medium access in 802.11 based wireless ad-hoc networks. In: 2000 First Workshop on Mobile and Ad Hoc Networking and Computing, Mobihoc 2000, pp. 99–106 (2000)
2. Bian, D., Zhang, H., Peng, S.: An improved protocol of ad hoc based on multi-channel statistics on mac layer. J. Air Force Eng. Univ. (Natural Science Edition) **14**(1), 80–84 (2013)
3. Chlamtac, I., Conti, M., Liu, J.N.: Mobile ad hoc networking: imperatives and challenges. Ad Hoc Netw. **1**(1), 13–64 (2003)
4. Clark, S.M., Hoback, K.A., Zogg, S.J.F.: Statistical priority-based multiple access system and method (2010)
5. Collins, R.: Tactical targeting network technology (TT-NT) (2008). https://www.rockwellcollins.com/Products-and-Services/Defense/Communications/Tactical-Data-Links/Tactical-Targeting-Network-Technology.aspx
6. Gao, X., Yan, J., Lu, J.: Priority weighted rate control algorithm in aeronautical ad hoc networks. Qinghua Daxue Xuebao/J. Tsinghua Univ. **57**(3), 293–298 (2017)
7. Gao, X., Han, F., Yan, J., Lu, J.: Collision model providing qos guarantee for the feedback-free MAC in aeronautical ad hoc networks. J. Beijing Univ. Aeronaut. Astronaut. **42**(6), 1169–1175 (2016)
8. Guo, D., Zhang, L.: Virtual full-duplex wireless communication via rapid on-off-division duplex. In: Communication, Control, and Computing, pp. 412–419 (2010)
9. Haas, Z.J., Deng, J., Liang, B., Papadimitratos, P., Sajama, S.: Wireless ad hoc networks. IEEE J. Sel. Areas Commun. **17**(8), 1329–1332 (2007)
10. Sakhaee, E., Jamalipour, A., Kato, N.: Aeronautical ad hoc networks. In: 2006 Wireless Communications and Networking Conference, WCNC, pp. 246–251 (2006)
11. Wang, Y.Q., Yang, F., Huang, G.C., Zhang, H.Y., Guo, J.X.: Media access control protocol with differential service in aeronautical frequency-hopping ad hoc networks. J. Softw. **24**(8), 2214–2225 (2013)
12. Zhang, H., Peng, S., Zhao, Y., Bian, D.: An improved algorithm of slotted-aloha based on multichannel statistics. In: Fifth International Symposium on Computational Intelligence and Design, pp. 37–40 (2012)
13. Zhou, S.: On the MAC protocol of TTNT. Ph.D. thesis, Xidian University (2015)