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Study on Key Techniques of Aeronautical Ad Hoc Network MAC and Network Layer

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Abstract

This paper studies on key techniques of aeronautical ad hoc network MAC and network layer based on the analysis of aeronautical ad hoc network application requirements as well as its own characteristics. MAC core processing architecture and binary exponential back-off algorithm based on QoS are designed based on the analysis of the SPMA state flow. Network layer core architecture is designed in view of the network layer functional requirements, and several key technique points such as network synchronization, network admittance and routing maintenance are designed and analyzed. The simulation results show the effectiveness of the design in this paper, and the design has a positive significance for designing of new concept aviation wireless communication products based on network centric warfare.

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Keywords: Aeronautical Ad Hoc Network; Statistical Priority-based multiple access; Shortest Path First; Collaborative Network.

1. Introduction

As the future development direction of aircraft cooperative data-link, aeronautical ad hoc network (AANET) creatively applies mobile ad hoc network between aircrafts, which enables ground control information and air perceive information communion among each other [1]. Other than the general characteristics inherent in MANET,

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such as multi hop, self-organizing and no center, aeronautical ad hoc network has its own unique characteristics [2], mainly includes: large scale and three-dimensional distribution scene, highly dynamic topology, instable channel quality, sparse nodes distribution, heterogeneous multi matter and temporality. Typical international aeronautical ad hoc projects includes: the Minuteman project of American Navy, the TTNT project of America Department of defense and air force, the ATENAA project of Germany, Greece etc, the AANET project of Australia and the EU NEWSKY project [3]. Aeronautical ad hoc network used in aircraft cooperative data link has the following advantages: offset long-distance and low altitude communication blind area of V/UHF band, improve the survivability of military aviation communication system, support tactical cooperative of aircraft formation. In order to adapt to fast, efficient, strong survivable air space ground integrated combat information platform of the future battlefield [4], it is essential to carry out the research on key techniques of collaborative aviation data-link, with the aeronautical ad hoc network as the kernel.

2. Key technical analysis

Aeronautical ad hoc network is a special MANET, which needs to consider moving model, formation division, channel access, routing maintenance etc, and should be made corresponding layered design according to its own characteristics. The efficient operation of MAC and network protocol are based on reasonable physical layer design, physical layer of this design uses GMSK modulation, Turbo error correction coding, burst communication system and multi user detection techniques to support the MAC layer and network protocol. Simultaneity, the physical layer uses frequency hopping carrier modulation technique to modulate different burst to different carrier according to the frequency hopping pattern. The time hopping technique is adopted to distribute transmission time of data burst. Frequency hopping and time hopping system can greatly reduce the collision probability of network. This paper mainly aims at the research of MAC and network layer key techniques of aviation data-link network, and verification of the design's effectiveness by Qualnet network simulation platform, the specific physical layer design is not included.

2.1. MAC layer design

The wireless channel of aeronautical ad hoc network is multi hop sharing channel, MAC protocol controls nodes to access the wireless channel, and plays a vital role on the network performance. Presently typical MAC protocol adopted by aeronautical ad hoc network includes the SPMA (Statistical Priority Multiple Access) protocol of TTNT [5] and the TDMA protocol of most other projects. This paper designs protocol implementation core architecture and key algorithm based on the analysis of SPMA protocol state flow chart.

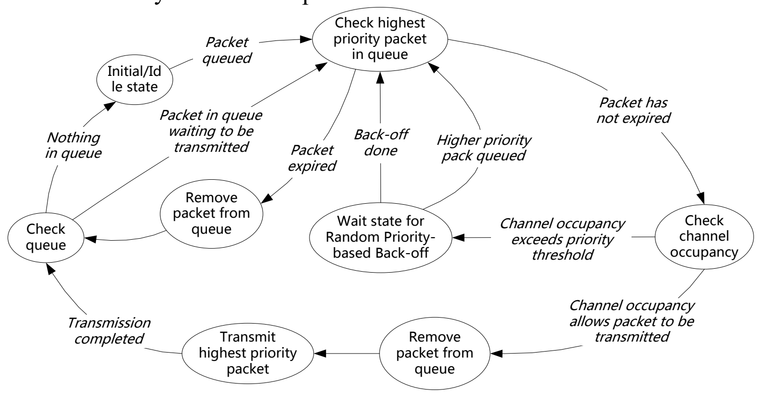

Fig. 1. SPMA processing state flow chart.

The core of SPMA [6] protocol is priority access technique based on statistics of channel occupancy state, namely countering the number of burst intercepted in channel over a period of time, and making comparison with channel accessing threshold. The SPMA state transition process is shown in Fig. 1, each node is independent and follow the same state transition strategy. The method of access protocol to solve "the signal collision" is controlling transmission of different priority data packets based on statistics of channel congestion degree and comparison of this degree to the packet's channel accessing threshold, this ensures low delay, high reliable transmission of high priority service, and ensures transmission of low priority service to the greatest extent by making full use of the channel transmission capacity based on the back-off algorithm simultaneity. Compared with CSMA [7] protocol, SPMA reduces the waiting time for information before accessing channel (no handshaking mechanism), on the other hand, it provides different message prioritization, and can guarantee the success accessing probability of high priority messages.

This paper designs core architecture of MAC layer shown in Fig. 2 based on SPMA core processing state transfer course, mainly including service priority queue management, traffic statistics, service access scheduling and control, as well as the data framing and de-framing module of MAC layer.

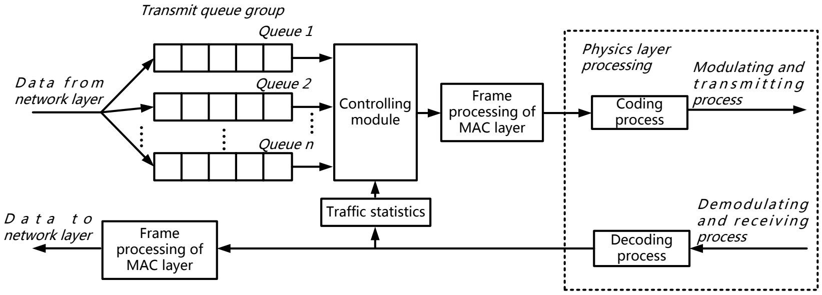

Fig. 2. Core architecture of statistical priority access algorithm.

In this design, when the accessing request conflicts, nodes are not allowed to access the channel immediately, and nodes need to select a random waiting time before transmitting. Waiting time calculation method can be the p-continuous probability random back-off, and also can be the binary exponential back-off. The performance comparison is shown in Fig. 3. This design adopts the binary exponential back-off method, for it has better adaptability to different network load conditions.

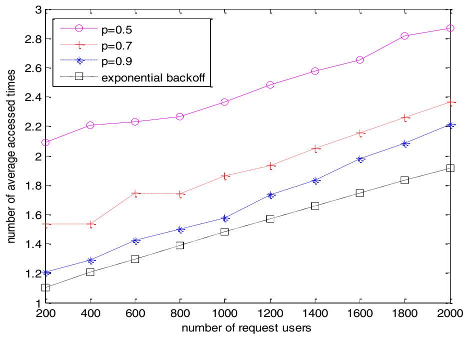

Fig. 3. Comparison of P-continuous and binary exponential back-off.

QoS requirements of different services should be considered in real application, so the influence of QoS parameters are considered during the design of the binary exponential back-off method. The design of binary exponential back-off method based on QoS requirements is as follows.

Assuming conflict window W, minimum conflict window W_{min}, maximum retransmission number M, QoS index k (greater value means lower QoS priority), current retransmission number m, then the current conflict window is:

$$W = \max\left(1, \left\lfloor \frac{k}{10} rand\left(2^m W_{\min}\right)\right\rfloor\right), m \le M \tag{1}$$

Here $\lfloor \bullet \rfloor$ indicates rounding down.

2.2. Network layer design

The existing MANET routing protocols cannot adapt to the frequent route change of aeronautical communication environment, AODV, DSR and other on-demand routing protocol used in aeronautical ad hoc network routing discovery will bring long delay, and prior routing protocol such as DSDV will lead to large amount of network spending and slow convergence speed. TTNT adopts OSPF (Open Shortest Path First) routing protocol [8], but the improvements and optimizing details cannot be obtained for key techniques of TTNT are strictly blockaded.

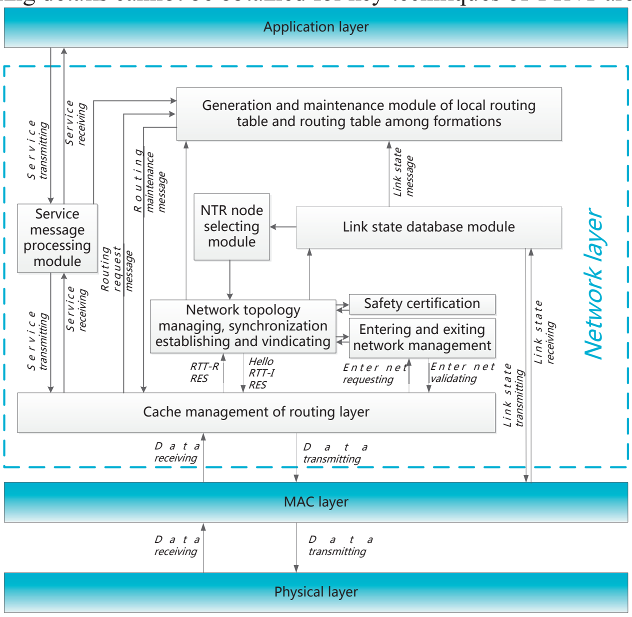

Fig. 4. Core architecture of network layer protocol realization.

According to the large spatial scale of aeronautical cooperative data-link, and attacking time sensitive characteristic, if on-demand routing protocol is adopted, the design goal will be hard to achieve. At the same time, although the vehicle nodes have high mobility, but the internal formation network topology can remain stable relatively, so as to avoid network topology rapid change due to high mobility in internal formation, and defects such as maintenance overhead and no convergence of table-driven routing protocol. This paper designs Formation-Based Open Shortest Path First(FBOSPF) routing protocol, according to the plane network topology and the network composed of manned/unmanned aerial vehicle formations, table-driven routing mode is adopted in internal formation, and on-demand routing mode among formations. FBOSPF routing protocol is based on link state information, not node distance vector. In view of functional requirements of the network layer, core architecture of the single node network layer is designed as shown in Fig. 4.

Analysis of several key techniques such as network synchronization, entering network process and routing maintenance of the designed network protocol are as follows.

2.2.1. Network synchronization

Network synchronization is precondition of the normal network operation, and the process should include inner formation synchronization and synchronizations among formations. The communication content among formations mainly includes situation awareness and performance feedback information in the actual network, the business volume is small and the real-time requirement is not high, so application scene and realization complexity is considered in this design, the synchronization accuracy among formations depends on the timing accuracy of each formation, no additional design is performed. Synchronization inner formation includes two stages of coarse clock synchronization and precise clock synchronization. Broadcast synchronization is performed first when the inner formation clock synchronization started, namely the NTR (network timing reference) node of formation transmits synchronization information, and members of the formation update local clock correspondingly. Respondent synchronization inner formation will be performed after broadcasting of inner formation synchronization, NTR node of formation should continue to determine whether there is a precise clock synchronization request after one respondent synchronization process inner formation is executed, if any, continue to execute respondent synchronization inner formation, otherwise, precise clock synchronization is completed.

Network synchronization principle is shown in Fig. 5, the synchronize node A finishes clock synchronization with time reference node B through time request and reply message. Known $T1$, $T2$, $T3$ and $T4$, time difference θ between the synchronize node A and time reference node B need to be achieved to adjust time of node A by the following equations:

$$\begin{cases} T2 = T1 + U1 + \theta \\ T4 = T3 + U2 - \theta \end{cases} \tag{2}$$

Assume sending and reply synchronization messages cost the same time during the path, namely $U1$ approximately equal to $U2$, thus θ can be obtained by solving the following equation:

$$\theta = \frac{(T2 - T1) - (T4 - T3)}{2} \tag{3}$$

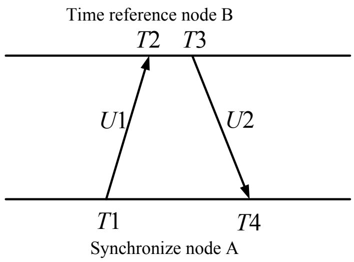

Fig. 5. Principle diagram of network synchronization.

Network synchronization precision depends on demodulation timing synchronization accuracy of the physical layer data and the difference calculated by sending and reply time of two aeronautical node's synchronization messages during the path. Time difference influences network synchronization precision, this paper mainly analyses this influence, and the producing process of this time difference is contained in a complete end to end message transmission. End to end delay of message mainly includes the high-level protocol processing delay, physical layer processing delay and propagation delay etc. Consider that the system meets the longest delay $2ms$, if the time difference Δt induced by message sending and receiving during the path is $2ms$, and assume that the relative speed v between two aeronautical nodes is $300m/s$, then the influence to the synchronization accuracy of network is as follow:

$$\frac{v * \Delta t}{c} = 2ns \tag{4}$$

Assuming that the synchronization cycle is *T*, then distance variation between two time synchronization request messages of two aeronautical nodes is *vT*. Assume the radial speed of two nodes is *v*, and *c* as the propagation velocity of electromagnetic waves, *t* as the sending time of one unidirectional synchronization message between two nodes after the second synchronization request. One synchronizing process schematic diagram between NTR node of formation and a common node is shown in Fig. 6. When the synchronization precision is set as $2t$=30*ns*, the relationship between synchronization cycle *T* and the radial velocity of the two nodes *v* is shown in Fig. 7. We can see from Fig. 7 that with the increasing of two nodes' radial velocity, if synchronization precision should keep unchanged, the synchronization cycle must be shortened correspondingly.

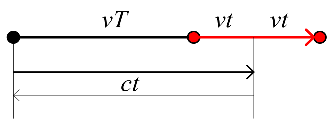

Fig. 6. Schematic diagram of synchronous cycle calculation.

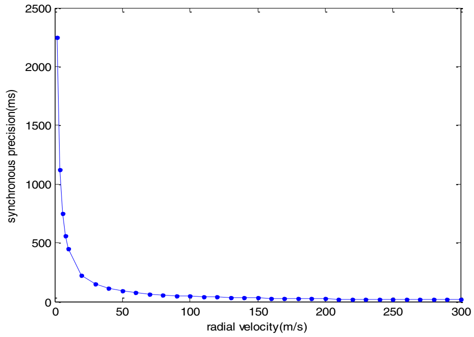

Fig. 7. Relationship diagram of synchronous cycle and radial velocity (precision of 30ns).

Time difference of air interface transmission induces little effect to network synchronization by the analysis above, and network synchronization precision mainly depends on signal demodulation timing synchronization accuracy of the physical layer. The actual network synchronization cycle can be calculated based on synchronization precision index, and second level can basically meet the needs.

2.2.2. Network entering process

According to the actual scene, the aeronautical cluster will need the air force support. Command center can direct a single aircraft to join a formation in order to increase the formation's combat capability based on the battlefield situation. This single aircraft cannot join the other formation optionally for this would disturb combat deployment. Aircraft formation can also join the aeronautical cluster according to the requirements of the Command center and increase the overall combat capability of cluster.

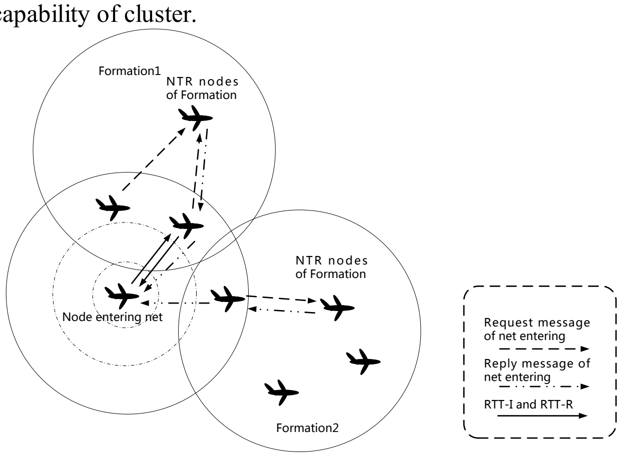

Fig. 8. Schematic diagram of single node entering network.

Due to the particularity of this network, the network entering process cannot interfere with normal communication of the network, so waiting for network accessing invitation passively is implemented in this design. All the nodes in the network periodically broadcast network invitation message, and in order to avoid network congestion, the waiting period of time with stochastic window mode is adopted, namely the node enters a stochastic window and selects a time slot to send invitation after waiting for a fixed period of time. Survival time of network invitation broadcast (TTL) is set to 1 in order to prevent the node transmitting invitation message, and this can also reduce message flooding. If the aircraft to enter the network receives the invitation message, it will reply network application according to the source node address information (Src_ID) contained in the message, and if more than one invitation message is received in a cycle, the aircraft only replies invitation firstly received. Nodes in network reply confirmation message after receiving the network access application message replied by the node to enter the net, add the node to the neighbor table and update the local routing table. Then the nodes in network inform the new accessing node through broadcasting the new neighbor table and routing table, and the node confirms network accessing application by receiving the confirmation message. The node to access the net receives the neighbor table and routing table updating broadcast, updates the local neighbor table and routing table, and the network accessing process is complete. Typical network accessing process scenario of single node is shown in Fig. 8. In order to adapt to the battlefield situation, cycle of network accessing invitation message could be changed accordingly. If the network accessing main body is aircraft formation, the operation of network accessing is done mainly by the NTR node of the formation, similar to the single node network accessing process. Network organizing inner formation will be processed after the procession of NTR node network accessing process.

2.2.3. Routing maintenance

Routing maintenance is divided into routing maintenance inner formation and routing maintenance among formations according to whether the destination node is in this formation. The following are pertinence design of routing protocol inner formation and routing protocol among formations.

2.2.3.1. Routing inner formation

For plane network structure is adopted in this design, topology information inner formation is periodically broadcasted by NTR node to other nodes of the formation. Therefore nodes inner formation knows topology information of the formation, and can finish routing lookup by transcendent routing protocol based on shortest path first rule. When a node needs to send packet to nodes inner the same formation, it will send the packet directly to the next hop node according to local routing information. Intermediate nodes received this data will determine the next hop node according to local routing table and the destination node of the packet. This paper designs routing protocol inner formation based on link state, and consider the link state including the signal quality and network congestion degree. The signal quality here considers *SNR* of the received signal, all of the *SNRs* is divided into 10 levels, *SNR* level is expressed by *LSNR*, where the lowest level means data cannot be correctly received. Network congestion degree is expressed by wireless channel occupancy rate *Pb*. If single transmitting and multiple receiving is considered, wireless channel occupancy rate need to be normalized according to the number of receive channels, namely channel congestion degree is expressed as $Pb=\text{sum}(Pt)/n$, where *Pt* is the transmission probability of different neighbor nodes, and *n* is the number of the receiving channels.

All nodes obtain link state of each node based on the receiving signal quality and network congestion degree, and store it into the link state database. The weighted shortest path algorithm is directly used for routing table calculation when communication with the node inner formation is in need. Link state table of each node is shown in Fig. 9. Unidirectional links should be supported in the design, so the link state of each unidirectional link needs to be stored separately.

Source Node ID	Neighbor ID	SNR Level	Channel Busy Ratio
Source Node ID 1	Neighbor ID 1	*SNR* Level	Channel Busy Ratio
	Neighbor ID 2	*SNR* Level	Channel Busy Ratio
	⋮	⋮	⋮
	Neighbor ID *N*	*SNR* Level	Channel Busy Ratio
⋮			
Source Node ID *M*	Neighbor ID 1	*SNR* Level	Channel Busy Ratio
	Neighbor ID 2	*SNR* Level	Channel Busy Ratio
	⋮	⋮	⋮
	Neighbor ID *N*	*SNR* Level	Channel Busy Ratio

Fig. 9. Table of link state information.

Destination Node ID	Next Hop Node
1	*X*
2	*X*
⋮	
N	*X*

Fig.10. Table of inner formation routing.

The node calculates the weights of the data-links to other nodes in the formation according to the node link state information obtained locally. Assume that all paths from the source node s to the destination node d are expressed as $P(s, d)$, where $l(s, d)$ is one path, and the corresponding weights are expressed as $w_l(SNR)$ and $w_l(busy)$ respectively, the coefficients are r_{snr} and r_{busy}, so the weight calculation formula is as follow:

$$W(s,d) = \min_{l(s,d)\in P(s,d)} \gamma_{snr} * w_l(SNR) + \gamma_{busy} * w_l(busy) \tag{4}$$

When the link state updates, routing layer of nodes calculates new routing paths to the relative nodes based on the new link state information, and save the results in the routing table. Routing table inner formation is shown in Fig. 10. Here X denotes the next hop node to the destination node.

2.2.3.2. Routing among formations

For maintenance of the whole network topology information will occupy massive channel resources, this design adopts routing protocol among formations of reaction type, and implementation process of the protocol is as below. When the node inner formation cannot find known routing to the destination node, it will initiate routing lookup message. For flooding broadcast of routing lookup messages will lead to the waste of resources, this design adopts boundary broadcasting mode to constrain the communication range of the routing lookup message. The intermediate nodes through which routing lookup messages passed add own ID information and link state into routing lookup messages, and transmit it to the next hop node. When routing lookup messages arrive at the destination node, the destination node sends routing confirmation message back along the original path according to the routing information recorded in routing lookup messages. The intermediate nodes through which routing confirm messages passed update the local routing table according to routing information carried by routing confirmation messages. When routing lookup information arrives at an intermediate node which knows the routing information to the destination node, this node will add the local routing information known to routing table in the routing message, and return the routing confirm message to the source node. The routing lookup message may pass through multiple paths to the destination node or transmitting intermediate nodes, the destination node and transmitting intermediate nodes will select the most appropriate return path according to the link states. In addition, for the actual network usually need to updates the network topology information with relatively long cycle in order to ensure cooperative work of each node, this design constrains broadcast range of routing lookup messages based on network topology information further.

<table>
<tr><td>Source Node ID</td><td colspan="2">Ref. Node of Source</td><td colspan="2">Destination Node ID</td></tr>
<tr><td>Query ID</td><td>Time To Live (TTL)</td><td colspan="2">Sent Time</td><td>Type</td></tr>
<tr><td colspan="5">Previous Routing Information</td></tr>
<tr><td>Forward Node ID</td><td colspan="4">Link Weight from the Previous Hop</td></tr>
</table>

Fig. 11. Updating structure of intermediate node's routing query message.

A routing query request to the destination node is sent to the NTR node of formation by routing protocol among formations firstly, and the NTR node decides the boundary node to which this routing query request packet will be transmitted according to the request and network topology information known. The boundary node transmits the routing request packet to the boundary nodes of adjacent formations. The neighbor nodes judge if the destination node is in the same formation after receiving the request packet, if so, the routing request packet will be sent to the destination node, or the routing information to the destination node will be returned directly. If not, boundary nodes repeat the process above, and send the routing request packet to the NTR node of the formation, the NTR node determines to which boundary nodes the request packet should be transmitted.

<table>
<tr><td>Source Node ID</td><td colspan="2">Ref. Node of Source</td><td colspan="2">Destination Node ID</td></tr>
<tr><td>Query ID</td><td>Time To Live (TTL)</td><td colspan="2">Sent Time</td><td>Type</td></tr>
<tr><td colspan="5">Previous Routing Information</td></tr>
<tr><td>Boundary Node ID 1</td><td colspan="4">Link Weight from the Previous Boundary Node</td></tr>
<tr><td>Boundary Node ID 2</td><td colspan="4">Sum of Link Weight from the Previous Boundary Node</td></tr>
</table>

Fig. 12. Updating structure of the boundary node's routing query message.

In order to avoid routing query request broadcasting reversely and forming a routing loop, this design assigns an ID to each query, and each intermediate node received the ID will store the ID in the local routing record table, and if the routing packet with same ID is received, it will be directly discarded instead of transmitting forward.

Due to the demise of the destination node, or the restriction of boundary nodes' transmitting scope, the route information may not be able to find, therefore TTL need to be set in routing lookup packets, TTL is reduced by 1 after each transmitting process, so as to limit the transmitting times of the routing lookup packets. Simultaneously, the routing lookup timer is set at the source node, if the timer expires, new routing lookup packet will be sent, and the boundary transmitting constraint options will be indicated to close, routing search will be performed through the network wide broadcast.

3. Simulation analysis

The design uses Qualnet network simulation software for modeling aeronautical ad hoc network, and analyzes performance of the system. The three-dimensional simulation scene is shown in Fig. 13. There are 17 nodes inside the network distributed with the boundary range of 700*km**700*km*, of which two formations are composed of 8 manned aerial vehicles, one formation is composed of 8 UAVs, and another early warning aircraft forms a formation solely. Manned aerial vehicle formations locate at the altitude of 5000*m*, and the UAV formations at the altitude of 3000*m*, while the early warning aircraft at the altitude of 8000*m*, Nodes move in the simulation region in accordance with the mobile model set in advance when the simulation starts.

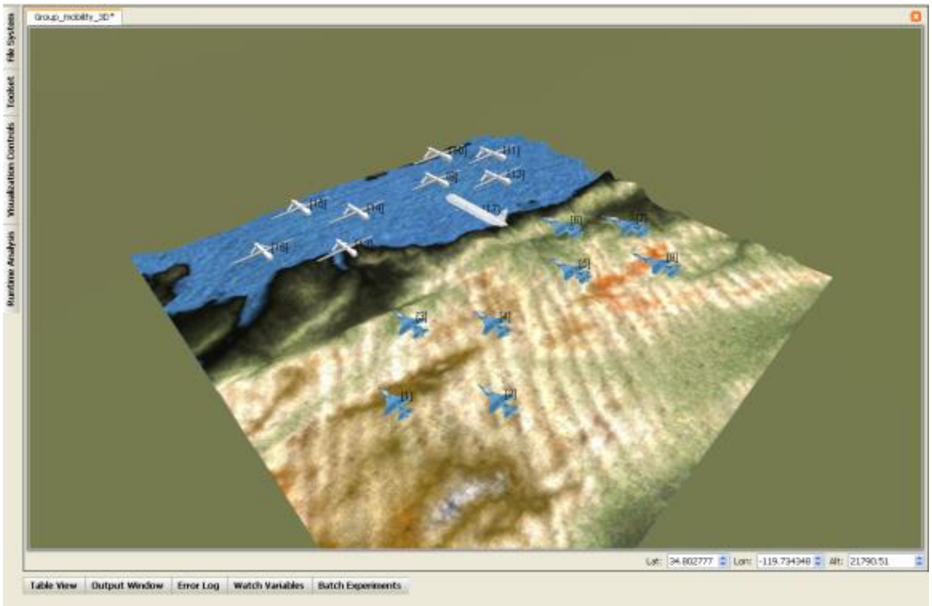

Fig. 13. Three dimension aeronautical ad hoc network simulation scenarios.

Consider characteristics of aeronautical ad hoc network such as large scale networking scene, three dimensional, high dynamic topology and sparse nodes distribution, simulation parameters of the scene are set as follows:

Table 1. Simulation parameters.

Network area	700*km*×700*km*	**Transmit power**	53*dBm*	**Fading model**	N/A
Network scale	17nodes	**Sensitivity**	-94*dBm*	**Receive antenna**	Omni-directional
Simulation time	60*min*	**Channel model**	Free space	**Mobile model**	Group Mobility
Physical model	Abstract model	**Transmitting gain**	0*dB*	**Access**	SPMA
Bandwidth	2.25*Mbps*	**Transmit antenna**	Omni-directional	**Routing**	OSPF
Frequency	1.35*GHz*	**Receiving gain**	0*dB*	**Application**	MPBS

Table 2. Setting of node formation and mobility parameters.

Formation number	**Node type**	**Formation node**	**Speed**	**Formation range**
0	Manned aerial vehicle	1~4	200*m/s*~400*m/s*	350*km*×350*km*
1	Manned aerial vehicle	5~8	200*m/s*~400*m/s*	350*km*×350*km*
2	Unmanned aerial vehicle	9~16	100*m/s*~200*m/s*	700*km*×350*km*
3	Early warning aircraft	17	200*m/s*~300*m/s*	350*km*×350*km*

The simulation analysis indicates that the key techniques adopted in this design are in normal working throughout the network operation, indexes such as average end-to-end delay, packet delivery ratio, average jitter and throughput of network all meet the design requirements. Take packet delivery ratio and average end-to-end delay as example, packet delivery rate is calculated by the ratio of receiving packet number of the destination node and sending packet number of the source node, the average end-to-end delay includes delay of route discovery, queue cache and channel transmission, and this can reflect the validity of the whole network. Simulation results and analysis are described as below.

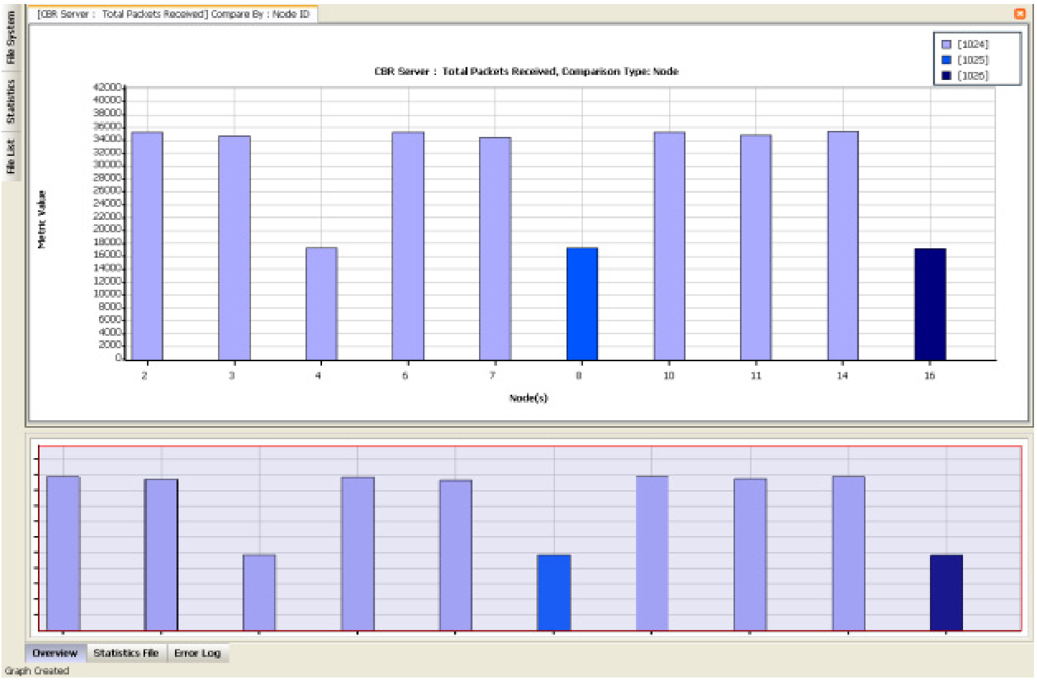

Fig. 14. Total receiving packet number of node.

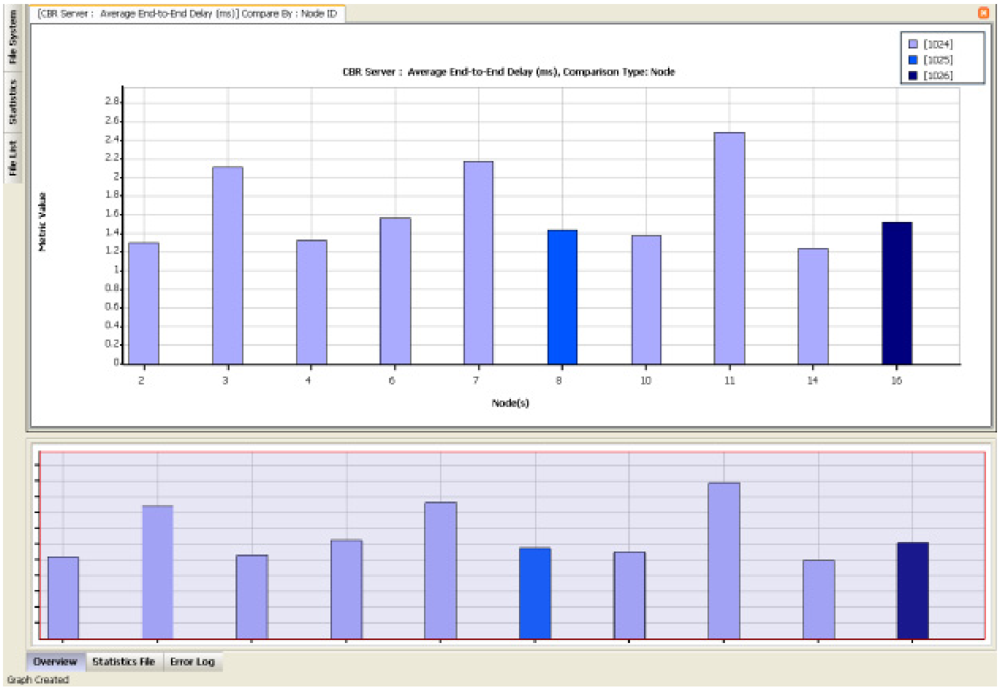

Fig. 15. Average end-to-end delay of node.

Table 3. Statistics of node's packet delivery ratio and average end-to-end delay.

Operation type	Source	Destination	Priority	Packets sent	Packets received	Receive ratio	Average end-to-end delay
Inner formation	1	2	low	35400	35309	99.74%	1.296*ms*
	5	6	low	35400	35292	99.69%	1.561*ms*
	9	10	low	35400	35316	99.76%	1.377*ms*
	13	14	low	35400	35388	99.97%	1.241*ms*
Among formations	3	7	low	35400	34406	97.19%	2.169*ms*
	7	11	low	35400	34846	98.44%	2.484*ms*
	11	3	low	35400	34738	98.13%	2.111*ms*
	17	4	high	18000	17850	99.17%	1.323*ms*
	17	8	high	18000	17826	99.03%	1.438*ms*
	17	16	high	18000	17741	98.56%	1.523*ms*

The simulation result indicates that low priority packets inner formation and high priority packets among formations exhibit a higher packet delivery ratio, while low priority packets inner formation exhibit a lower ratio. For group mobility model is adopted by nodes in the network, the relative position of nodes inner formation changes slowly and the network topology inner formation keeps stable, packets inner formation can keep higher delivery rate. But the relative position of nodes among formations changes rapidly, the rapid changing of network topology leads to frequent routing failure and data loss.

The longer transmission delay between nodes and multi hop routing delay cause the longer delay of low priority packets among formations indicated by the simulation result, and low priority packets have longer access waiting time due to the existence of high priority packets. For the amount of low priority situation awareness packets among formations is small and the real-time requirement is not strict in the actual work situation, this design accord with expectations.

4. Conclusion

This paper studies on corresponding key techniques of aeronautical ad hoc network MAC and network layer, and completes key techniques design, system modeling and simulation. The simulation results prove the validity of this design. Key techniques in this design can improve network data transmission and task cooperative performance of the aeronautical cluster, and has important reference value for the aeronautical network data-link application.

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