



Bidirectional Scanning Based Medium Access Control Algorithm in Directional Aviation Relay Network with Multiple Air Nodes

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Abstract. Directional aviation relay networks are widely used to improve the performance of ad hoc networks. Aiming at the disadvantage of large data packet delay of directional aviation relay network with single air node, this paper proposes a medium access control algorithm based on multiple air nodes and bidirectional scanning, which can effectively reduce the total delay of data packets. First, the algorithm divides multiple air nodes into two groups, using clockwise and counterclockwise scanning modes respectively, to provide data relay and forwarding services for ground nodes. According to the number of air nodes and their scanning mode, as well as the sector in which the destination node of the to-be-sent traffic is located, the ground nodes determine whether the to-be-sent traffic uses a single-aircraft relay two-hop transmission or a double-aircraft relay four-hop transmission link in a distributed manner. Secondly, the theoretical model of unidirectional scanning and bidirectional scanning algorithm is built, and the theoretical packet delay distribution law of the two algorithms as well as the optimal ratio of bidirectional scanning algorithm in reducing packet delay compared with unidirectional scanning algorithm is obtained. Finally, the performance of the proposed algorithm is verified by simulation. The simulation results are consistent with the theoretical analysis, which show that in the case of 4 to 8 air nodes, compared with unidirectional scanning algorithm, the total delay of packets in bidirectional scanning algorithm is reduced by 23.10%–28.81%.

Keywords: directional aviation relay network · multiple air nodes · MAC · data packet delay

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1 Introduction

Due to the limitation of energy of nodes in network, wireless ad hoc networks have shortcomings in terms of transmission power and transmission distance, especially in long-distance networks and scenarios where the line of sight is blocked by terrain, so it is difficult to guarantee the quality of point-to-point communication between the source node and the destination node. Therefore, relay technology is widely used in wireless ad hoc networks to improve the link state between the source node and the destination node and expand the coverage of the network. A network that uses small unmanned aerial vehicles as a relay platform to carry directional wireless network communication equipment to assist ground nodes in data transmission in network scenarios with large spans, such as in articles [1, 2], is called a directional aviation relay network (DARN). The drones in it are called air nodes.

The directional aviation relay network has the advantages of widening network coverage, improving network throughput, facilitating network management, reducing packet delay and being easy to deploy. However, its medium access control protocol design also faces severe challenges such as increased propagation delay and increased collision probability.

For the medium access control technology of directional aviation relay network, the existing research in [2–11] mainly focuses on reducing collision probability, avoiding channel competition, optimizing link distance and making full use of the interval between sending and receiving packets caused by propagation delay. In [2] Yan Z J et al. proposed a medium access control protocol that divides the network scene according to the link distance from the ground node to the air node. In order to solve the problem of the efficiency reduction of medium access control protocol caused by the increase of propagation delay, in [6–8] Zhou W L et al. designed an environment adaptive medium access control protocol using the TBAG protocol framework that is controlled and triggered by the air node in the scenario of deploying a single air node. In [9] Xiafei Bu et al. proposed to use orthogonal frequency division multiple access technology to improve network efficiency considering the power consumption of UAVs. In [10] Muhammad Farhan Sohail et al. applied non-orthogonal multiple access technology to UAV relay network to improve the total network transmission rate and energy utilization and expand the network coverage. In [11] Jiangbin Lyu et al. proposed a cyclic multiple access protocol by using the periodic change of the signal strength between the UAV and the ground nodes during the circular motion of the UAV.

Resource allocation is closely related to medium access control technology. Because the idea of competing for network resource used by traditional DCF technology will cause waste of time resources in large-scale directional aviation relay networks, scholars at home and abroad have also conducted in-depth research on resource allocation algorithms applied to large-scale directional aviation relay networks. In [8, 9] Zhou W L et al. proposed an algorithm for time slot resource allocation based on the link distance based on TBAG protocol architecture. The air node uses the propagation delay of communication with the long-distance ground nodes to communicate with the short-range ground

nodes opportunistically, and makes a unified arrangement for the packet sending sequence of all the nodes in the network in the data transmission stage in current time frame. In [12] Daniel T. Bennett et al. proposed a shortest path first method to reduce network overhead by optimizing beam switching sequence and improve the throughput of ground nodes by optimizing time allocation of beams. In [13] Jin Li et al. proposed a resource allocation algorithm to improve resource utilization for cellular networks with multiple UAVs.

The current medium access control technologies proposed for directional aviation relay networks mainly focus on reducing packet collisions, improving medium access control efficiency, shortening packet propagation delays, or solving the adverse effects caused by increased packet propagation delay. But few literatures mentioned the optimization of packet delay, or the application of multi-air nodes deployment mode in reducing packet delay. Aiming at the problem of packet delay optimization, this paper proposes a bidirectional scanning medium access control algorithm for multi-air nodes scenario. The ground nodes sense the number of air nodes and their scanning mode, and determines in a distributed manner whether the traffic to be sent uses a single-aircraft relay two-hop transmission or a double-aircraft relay four-hop transmission mode according to the sector where the destination node of the traffic to be sent is located. Theoretical analysis and simulation verification confirm the performance of the medium access control algorithm proposed in this paper in optimizing packet delay.

This paper consists of six chapters. The first chapter introduces the research background and research significance of DARN. The second chapter introduces the directional aviation relay network model. The third chapter proposes a bidirectional scanning medium access control algorithm for multi-air nodes scenario. The fourth chapter analyzes the packet delay performance of the proposed algorithm theoretically. The fifth chapter verifies the performance of the medium access control algorithm proposed by simulation. And the sixth chapter is the summary and conclusion of the whole paper.

2 Network Model

The network coverage is a circular area with a radius of RD_1 . The ground nodes are evenly distributed in the network, and multiple air nodes that cannot communicate with each other directly do a uniform circular motion with a small radius of RD_2 around the center of the network. The air nodes can be regarded as stationary at the center of the network given that $RD_1 \gg RD_2$.

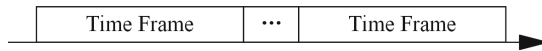


Fig. 1. Time frame structure.

In order to expand the coverage and reduce the interference range, the air nodes use directional antennas that can realize beam switching to cover the

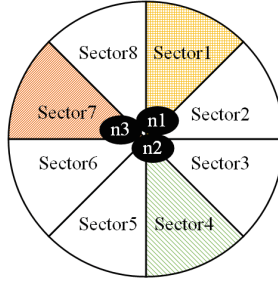


Fig. 2. Schematic diagram of multi-air nodes cover the network area.

ground network. There are N identical air nodes that can not communicate with each other in the network. The width of the directional beam divides the network into M sectors, and the time is divided into time frames of duration Δ as shown in Fig. 1. Each air node serves ground nodes in M sectors sequentially in a scanning manner, and each air node can only cover one sector in each time frame.

All nodes work in the same frequency band. Due to the problem of co-frequency interference, at most M air nodes can be deployed in the network, covering all the M sectors at the same time. And the beams of any two air nodes cannot cover the same sector at the same time.

Let $P(g, d)$ represents the data packet with ground node g as the source node and ground node d as the destination node. Let the sector where g is located be S_g , and the sector where d is located be S_d . Let each air node serve each sector for the same length of time, denoted as Δ . n represents the air node currently serving the sector where g is located. n' is the air node whose scanning mode is different from that of n and reaches the sector where g is located earlier than any other air nodes that has the same scanning mode with it. T_n^2 is the single-aircraft two-hop packet delay with air node n as the relay node, and $T_{n'}^2$ is the single-aircraft two-hop packet delay with air node n' as the relay node. Without loss of generality, assuming that the scanning mode of air node n is clockwise, while the scanning mode of air node n' is counterclockwise.

Figure 2 is a schematic diagram of a network scenario with 8 sectors and 3 air nodes, where $n1, n2, n3$ represents the 3 air nodes.

3 Bidirectional Scanning Medium Access Control Algorithm

3.1 Basic Idea

Because the destination nodes of the traffic flow of the source node are evenly distributed in all the sectors, the multi-air nodes medium access control algorithm proposed in this paper divides the air nodes equally into two groups. The first group performs counterclockwise beam scanning, and the second group performs clockwise beam scanning.

The medium access control algorithm proposed in this paper is called the bidirectional scanning algorithm. The medium access control algorithm using the traditional idea that all air nodes scan in the same direction and work independently without affecting each other is called the unidirectional scanning algorithm, and is used for performance comparison in this paper. On the basis of bidirectional scanning, this paper designs a four-hop relaying link where the data packet passes through source node, air node A, ground relay node, air node B and destination node in turn, to further reduce the packet delay.

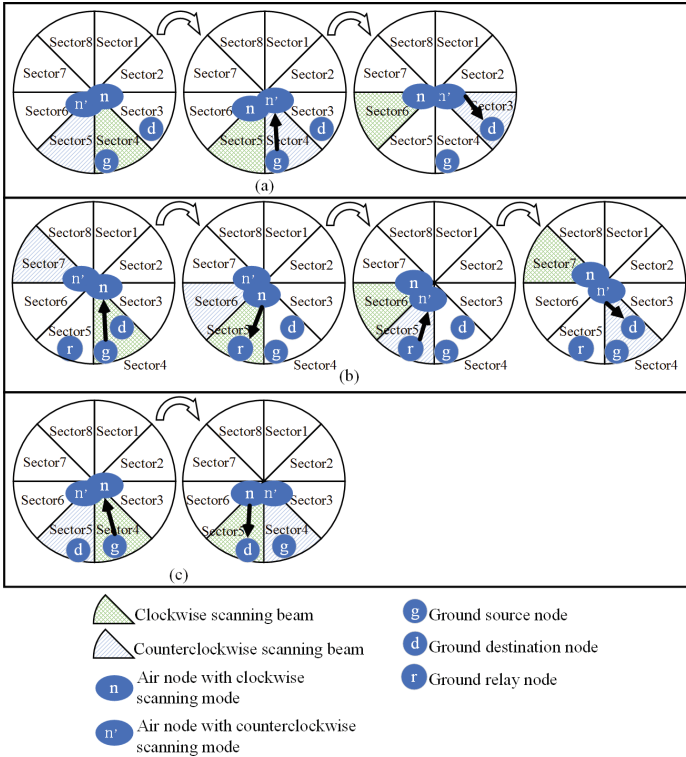


Fig. 3. Schematic diagram of packet delay optimization.

Figure 3 shows a schematic diagram of the idea of packet delay optimization. In scenario (a), if select the air node n' that scans counterclockwise for two-hop relay, only two beam rotations are needed to complete the packet transmission, which is better than selecting the air node n that scans clockwise. In scenario (b), a double-aircraft four-hop relay is used, node n receives the data packets from the source node, and sends them to the ground relay node when its beam rotates to sector 6, so that node n' can receive the data packets again when its beam rotates to sector 6 and send them to the destination node located in sector

5 when its beam rotates to sector 5. Only 3 beam rotations are required to deliver the packets to the destination node, which is better than the two-hop links that requires 8 beam rotations. In scenario (c), the data packet transmission delay can be minimized by directly passing the data packets through node n .

Because the air nodes cannot communicate with each other, each air node will serve M sectors in turn, instead of serving some of the sectors individually. Approximate analysis shows that the bidirectional scanning algorithm provides the source node with the option of transmitting data packets in the counterclockwise direction, thereby reducing the packet delay by half. If it is considered that the traffic flows need to be optimized by delivering in a counterclockwise direction, and the traffic flows that does not need to be delivered in a counterclockwise direction both accounts for 1/2 of the total traffic, then compared with the unidirectional scanning algorithm (donate its average packet delay with T_{Delay}), the bidirectional scanning algorithm can obtain a packet delay optimization ratio of about 25%:

$$\frac{T_{Delay} - (0.5 \times T_{Delay} + 0.5 \times 0.5T_{Delay})}{T_{Delay}} = 25\% \quad (1)$$

The air nodes need to maintain a ground node location table that records the MAC address of each ground node and the sector where it is located, and periodically broadcast to inform each ground node of sectors where all nodes in the network are located. Based on the number of air nodes and the scanning mode of each air node, combined with the sector where the destination node is located, the ground source node distributedly selects one from the three data packet transmission links, two single-aircraft relay two-hop transmission links and a double-aircraft relay four-hop transmission link, to reduce packet delay.

3.2 Algorithm Process Design

To facilitate the description of the algorithm, make the following definitions.

Definition 1. *Downlink data transmission request table (DL-REQ).* The downlink data transmission request table with the air node n as source node and ground nodes as destination node, including the column of destination node.

Definition 2. *Uplink traffic request table (UL-REQ).* A table formed by air node n by collecting the uplink traffic request of all ground nodes, including the column of relay mode (four-hop or two-hop) of the traffic, whether the air node is the last hop and destination node.

Definition 3. *Forwarding queue (FOR-QUE).* A queue composed of data packets with ground node g as relay node instead of destination node.

Definition 4. *Sending Queue (SEND-QUE).* A queue consisting of data packets that are most suitable to be relayed and forwarded by the air node n that is serving the sector according to the relay link selection algorithm.

Definition 5. *Downlink traffic response table (DL-RES). Air node n collects the downlink traffic response of all ground nodes into this table, which includes the column of destination node and whether to agree to receive downlink data.*

Algorithm 1. Bidirectional Scanning Multiple Access Algorithm.

Input:

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1. Number of air nodes ( $N$ ) and their scanning mode, 2.  $S_d$ 
1: while True do
2:    $n$  serves sector  $m$ , sends its own scanning mode and DL-REQ to the sector
3:   Ground node  $g$  receives information
4:   if  $g$  is included in the DL-REQ then
5:      $g$  replies downlink traffic response to  $n$ , ready to receive downlink traffic
6:   end if
7:   if (FOR-QUE of  $g$  is not empty) or (SEND-QUE of  $g$  is not empty) then
8:      $g$  sends an uplink traffic transmission request to  $n$ 
9:   end if
10:   $n$  receives responses from all ground nodes
11:  if  $n$  has packets as the 2nd hop source node in four-hop relay link then
12:    if The DL-RES of  $n$  is not empty then
13:       $n$  selects the nearest node in DL-RES as ground relay node of the four-hop
      relay link and inserts the traffic into the DL-RES
14:    else
15:       $n$  abandons the four-hop relay for these packets
16:    end if
17:  end if
18:   $n$  executes the resource allocation according to UL-REQ and DL-RES and broad-
  casts the time slot allocation result to ground nodes (the resource allocation
  algorithm described is not within the scope of this paper)
19:  Nodes transmit data according to resource allocation result
20:   $m = m + 1$  // Beam switching
21:  if  $m > M$  then
22:     $m = m - M$ 
23:  end if
24: end while

```

To facilitate the theoretical analysis of packet delay, the following definitions are made:

Definition 6. *Waiting delay. The time required from the generation of the data packet by the ground node to the reception of the packet by an air node.*

Definition 7. *Forward delay. The time required from the data packet generated by a ground node is received by an air node to the time when the data packet is received by the destination node.*

Because the two processes do not overlap in time, the discrete probability distributions of packet waiting delay and forward delay are statistically independent.

The data transmission process of bidirectional scanning algorithm is shown in Algorithm 1.

In Algorithm 1, in rows 2–10 the air node performs uplink and downlink traffic collection, in rows 11–18 the air node performs resource allocation based on the traffic collection results, in row 19 nodes perform data transmission, and the air node in rows 20–23 performs beam switching.

The ground nodes determine the sending queue through a distributed relay link selection algorithm, and the algorithm procedure is shown in Algorithm 2.

Algorithm 2. Relay Link Selection Algorithm.

Input:

Number of air nodes and their scanning mode

The sector where the destination node d is located

Output:

Selected relay link

- 1: **for** $P(g, d)$ in Data packet queue **do**
 - 2: Read packet destination address d
 - 3: **if** d and g are in the same sector **then**
 - 4: g selects air node n that currently serving the sector to perform double-aircraft four-hop relay
 - 5: **else**
 - 6: Calculate $T_n^2 = \Delta \times (S_{g \rightarrow clk} S_d) // S_{g \rightarrow clk} S_d$ is the number of sectors went through by clockwise scanning from sector S_g to sector S_d
 - 7: Calculate $T_{n'}^2 = \Delta \times (S_{n' \rightarrow aclk} S_{g \rightarrow aclk} S_d) // S_{n' \rightarrow aclk} S_g$ is the number of sectors went through from $S_{n'}$, the current serving sector of n' to the sector where g is located. $S_{g \rightarrow aclk} S_d$ is the number of sectors went through by counterclockwise scanning from sector S_g to sector S_d
 - 8: **if** $T_n^2 < T_{n'}^2$, **then**
 - 9: g selects n as the relay node for two-hop transmission and inserts the data packet $P(g, d)$ into the sending queue
 - 10: **else**
 - 11: g does not select n as the relay node
 - 12: **end if**
 - 13: **end if**
 - 14: **end for**
-

4 Theoretical Analysis of Algorithm Performance

4.1 Performance Analysis of Unidirectional Scanning Algorithm with Multi-air Nodes

Waiting Delay. It can be proved that evenly distributing the beams scanning in the same direction can make the maximum and average waiting delay of each sector reach the minimum value at the same time. That is, when the number of sectors is divisible by the number of beams, the beams are equally spaced, or when the number of sectors is not divisible by the number of beams, the beams

are approximately equally spaced. As shown in Fig. 2, the concept of unit is introduced, and N beams divide all sectors into N units, and the number of sectors in each unit is $\lfloor M/N \rfloor$ or $\lceil M/N \rceil$. The number of units containing $\lfloor M/N \rfloor$ sectors is $(M - N \lfloor M/N \rfloor)$, and the number of units containing $\lceil M/N \rceil$ sectors is $[N - (M - N \lfloor M/N \rfloor)]$. For example, in Fig. 2, 3 uniformly distributed beams divide 8 sectors into 3 units, and each unit has 3, 3 and 2 sectors respectively. The air nodes cannot communicate with each other, so each air node will serve M sectors in turn. Therefore, after M time frames, each sector is served N times, and after $\lceil M/N \rceil$ time frames, each sector will be served at least once. So $\lceil M/N \rceil$ is the upper limit of the waiting delay.

Because the ground nodes select the nearest air node to send the uplink data packets, and the source node needs at least one time frame to send the data packets to the air node, the value range of the waiting delay (in time frames) is $[1, \lceil M/N \rceil]$ and obey the uniform distribution. Its discrete probability distribution law is as follow.

$$P(T_{Wait}^{unidirectional} = t_{Wait}^{unidirectional}) = \begin{cases} \frac{N}{M}, t_{Wait}^{unidirectional} = 1, 2, \dots, \lfloor \frac{M}{N} \rfloor \\ \frac{M - N \lfloor \frac{M}{N} \rfloor}{M}, t_{Wait}^{unidirectional} = \lceil \frac{M}{N} \rceil \end{cases} \quad (2)$$

Forward Delay. Because in the unidirectional scanning algorithm, each air node is exactly the same. The ground nodes do not need to select the air nodes, so the packet transmission delay is only related to the number of sectors between the two sectors where the source node and the destination node are located. And its probability distribution law is:

$$P(T_{Forward}^{unidirectional} = t_{Forward}^{unidirectional}) = \frac{1}{M}, t_{Forward}^{unidirectional} = 1, 2, \dots, M \quad (3)$$

Total Delay. The probability distribution of the total delay of the data packet of the unidirectional scanning algorithm is equal to the distribution of the sum of the two independent random variables, the waiting delay and the forward delay. Its distribution and mathematical expectation of the total data packet delay of unidirectional scanning algorithm are as follow.

$$P(T_{Delay}^{unidirectional} = t_{Delay}^{unidirectional}) = \begin{cases} \frac{N \times (t_{Delay}^{unidirectional} - 1)}{M^2}, t_{Delay}^{unidirectional} = 2, \dots, \lfloor \frac{M}{N} \rfloor + 1 \\ \frac{1}{M}, t_{Delay}^{unidirectional} = \lceil \frac{M}{N} \rceil + 1, \dots, M + 1 \\ \frac{1}{M} - \frac{N \times (t_{Delay}^{unidirectional} - M - 1)}{M^2}, t_{Delay}^{unidirectional} = M + 2, \dots, \lceil \frac{M}{N} \rceil + M \end{cases} \quad (4)$$

$$E(T_{Delay}^{unidirectional}) = \left(1 - \frac{N}{2M} \times \left\lfloor \frac{M}{N} \right\rfloor\right) \times \left(\left\lfloor \frac{M}{N} \right\rfloor + 1\right) + \frac{1 + M}{2} \quad (5)$$

4.2 Performance Analysis of Bidirectional Scanning Algorithm with Multi-air Nodes

Analytical Method. The situation of the multi-air nodes bidirectional scanning algorithm is more complicated and it is difficult to carry out accurate performance analysis. Therefore, the analysis of bidirectional scanning algorithm is estimated based on the theoretical analysis results of unidirectional scanning algorithm. And the optimal ratio that can be obtained by bidirectional scanning algorithm compared with the unidirectional scanning algorithm in the average total delay of data packets is estimated. In two special scenarios, the 8-sector 4-air node scenario and the 8-sector 8-air node scenario, Matlab is used to enumerate all possible cases of the sector where the source node is located, the sector where the destination node is located, and the sector where the beam is located when the source node generates a packet in bidirectional scanning algorithm. All possible combinations of these three parameters are enumerated, the total packet delay of each case is obtained and the distribution law is calculated. The mathematical expectation is also obtained to test the estimation results.

Waiting Delay. Compared with the unidirectional scanning algorithm, the bidirectional scanning algorithm divides all air nodes into two groups, which provide relay services for ground nodes respectively. Since the destination nodes are evenly distributed in the network, the probability that the source node selects two groups of air nodes is considered equal. Therefore, the waiting delay of the bidirectional scanning algorithm is approximately twice that of the unidirectional scanning algorithm, and its distribution law is:

$$P(T_{Wait}^{bidirectional} = t_{Wait}^{bidirectional}) = \begin{cases} \frac{N}{2M}, t_{Wait}^{bidirectional} = 1, 2, \dots, \lfloor \frac{2M}{N} \rfloor \\ \frac{M - \frac{N}{2} \times \lfloor \frac{2M}{N} \rfloor}{M}, t_{Wait}^{bidirectional} = \lceil \frac{2M}{N} \rceil \end{cases} \quad (6)$$

Forward Delay. When the delay T_{Delay} of selecting an air node that scans clockwise is more than $M/2$, selecting another air node that scans counter-clockwise for relay may have a shorter forward delay of $(M - T_{Delay}) < M/2$. Therefore, it is approximated that the forward delay of the bidirectional scanning algorithm can be optimized to $1/2$ of the unidirectional scanning algorithm, and its distribution law is:

$$P(T_{Forward}^{bidirectional} = t_{Forward}^{bidirectional}) = \frac{2}{M}, t_{Forward}^{bidirectional} = 1, 2, \dots, \frac{M}{2} \quad (7)$$

Total Delay. The distribution law of the total packet delay in the bidirectional scanning algorithm can also be obtained by calculating the distribution of the sum of two independent random variables, the waiting delay and the forward delay. Its distribution law and mathematical expectation are as follow.

$$P \left(T_{Delay}^{bidirectional} = t_{Delay}^{bidirectional} \right) = \begin{cases} \frac{N \times (t_{Delay}^{bidirectional} - 1)}{M^2}, t_{Delay}^{bidirectional} = 2, \dots, \lfloor \frac{2M}{N} \rfloor + 1 \\ \frac{2}{M}, t_{Delay}^{bidirectional} = \lceil \frac{2M}{N} \rceil + 1, \dots, \frac{M}{2} + 1 \\ \frac{2}{M} - \frac{N \times (t_{Delay}^{bidirectional} - \frac{M}{2} - 1)}{M^2}, t_{Delay}^{bidirectional} = \frac{M}{2} + 2, \dots, \lceil \frac{2M}{N} \rceil + \frac{M}{2} \end{cases} \quad (8)$$

$$E (T_{Delay}^{bidirectional}) = \left(1 - \frac{N}{4M} \times \left\lfloor \frac{2M}{N} \right\rfloor \right) \times \left(\left\lfloor \frac{2M}{N} \right\rfloor + 1 \right) + \frac{1 + \frac{M}{2}}{2} \quad (9)$$

4.3 Performance Comparison of Unidirectional and Bidirectional Scanning Algorithms

For the mathematical expectation of the total packet delay, compared with the unidirectional scanning algorithm, the optimal ratio that the bidirectional scanning algorithm can achieve is:

$$\gamma = \frac{E (T_{Delay}^{unidirectional}) - E (T_{Delay}^{bidirectional})}{E (T_{Delay}^{unidirectional})} \quad (10)$$

In the 8-sector 4-air node scenario and the 8-sector 8-air node scenario, the estimated optimal ratios of bidirectional scanning algorithm are as follow.

$$\begin{aligned} \gamma|_{M=8,N=4} &= [(3/2 + 9/2) - (5/2 + 5/2)] / (3/2 + 9/2) = 1/6 \approx 16.67\% \\ \gamma|_{M=8,N=8} &= [(1 + 9/2) - (3/2 + 5/2)] / (1 + 9/2) = 3/11 \approx 27.27\% \end{aligned} \quad (11)$$

It can be seen that compared with the unidirectional scanning algorithm, the bidirectional scanning algorithm can further optimize the packet delay. In the scenarios of 8 sectors and 4 air nodes, and 8 sectors and 8 air nodes, the optimal ratio of bidirectional scanning algorithm compared with unidirectional algorithm obtained by computer is 19.27% and 31.82% respectively, which is close to the estimated result.

5 Simulation and Verification

5.1 Simulation Scene Construction

The performance of the proposed medium access control algorithm is tested and verified by using the NS3 simulation platform in the Linux operating system, and the performance of the two kinds of medium access control algorithms in the multi-air nodes scenario is compared.

The network range is equally divided into 8 sectors according to the directional beamwidth. The number of ground nodes are set to 16, 32 and 64 in turn, which are evenly distributed in all the sectors. The data packet generation of each traffic flow obeys the periodic process, and the destination nodes are also evenly distributed in all the sectors. And there are 1, 4 and 8 air nodes in turn. Therefore, there are 9 simulation scenarios in total, and the specific parameters are shown in Table 1.

Table 1. Simulation parameter notation and configuration.

Notation	Parameter meaning	Value
M	Number of sectors	8
N	Number of air nodes	1, 4, 8
Δ	Duration of a time period	15 ms
RD_1	Radius of network coverage	150 km
RD_2	Radius of the circular motion of air nodes	1 km

5.2 Simulation Results

The average packet delay of all simulation scenarios is shown in Fig. 4. When there are 4 air nodes in the network, the theoretical analysis results and simulation results of the packet delay probability distribution of the two algorithms are shown in Fig. 5. When there are 8 air nodes in the network, the theoretical analysis results and simulation results of the packet delay probability distribution of the two algorithms are shown in Fig. 6.

The average packet delay decreases with the increase of the number of air nodes. Compared with the single air node deployment scheme, the multi-air nodes deployment scheme can significantly reduce the average data packet delay. When there are 4 and 8 air nodes, compared with scenario with only one air node, the average packet delay of the bidirectional scanning algorithm is reduced by 85.39% and 89.47%, and the delay of unidirectional scanning algorithm is reduced by 82.39% and 85.21%, respectively.

The bidirectional scanning algorithm can further optimize the packet delay based on the unidirectional scanning algorithm. When there are 4 air nodes, compared with the unidirectional scanning algorithm, the bidirectional scanning algorithm reduces the average packet delay by 23.10%. And when there are 8 air nodes, compared with the unidirectional scanning algorithm, the bidirectional scanning algorithm reduces the average packet delay by 28.81%. The simulation results are consistent with the theoretical optimization ratios of 19.27% and 31.82%. In this paper, the duration of a time frame is used as the delay interval, and the percentage of data packets in each delay interval is counted. It can be seen from Fig. 5 and Fig. 6 that the packet delay distribution obtained by the simulation is consistent with the results obtained by the theoretical analysis.

In terms of throughput, compared with the single-air node scheme, the throughput of the multi-air nodes scheme is significantly increased, while the throughput of the bidirectional scanning algorithm is similar to that of the unidirectional scanning algorithm.

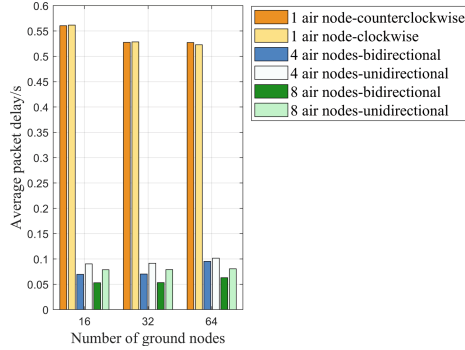


Fig. 4. Average data packet delay.

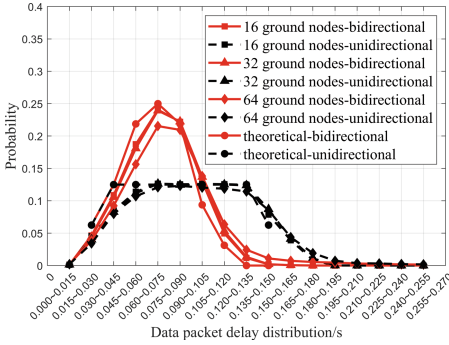


Fig. 5. Probability distribution of data packet delay with 4 air nodes.

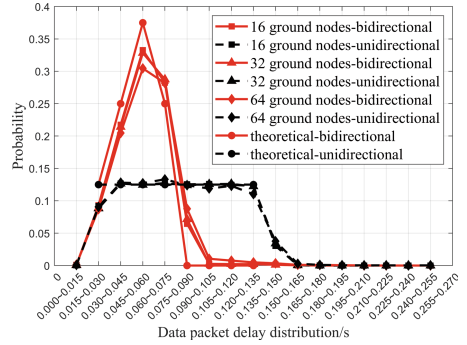


Fig. 6. Probability distribution of data packet delay with 8 air nodes.

6 Conclusion

In this paper, a multi-air node-oriented bidirectional scanning medium access control algorithm is proposed for the directional aviation relay network. The distributed relay link selection algorithm enables the ground nodes to dynamically adjust the data packet transmission link according to the number and scanning mode of the air nodes, shortening the total delay of data packets from the source node to the destination node. Simulation results demonstrate that multi-air nodes can significantly reduce packet delay and increase network throughput. And compared with the traditional unidirectional scanning algorithm, the bidirectional scanning algorithm proposed in this paper can further reduce the delay of packets. When the number of air nodes is not less than 4, compared with unidirectional scanning algorithm, the packet delay can be reduced by about 23.10%–28.81%. In terms of average packet delay and delay probability distribution, the simulation results are in good agreement with theoretical analysis.

References

1. Shake, T., Amin, R.: Maximizing interconnectedness and availability in directional airborne range extension networks. In: 2017 IEEE Military Communications Conference, Baltimore, pp. 273–278 (2017)
2. Yan, Z.J., Li, Q., Li, B.: A link distance division based time division multiple access protocol for directional aeronautical relay networks. *J. Northwest. Polytechnical Univ.* **38**, 147–154 (2020)
3. Zeng, Y., Zhang, R., Lim, T.: Wireless communications with unmanned aerial vehicles: opportunities and challenges. *IEEE Commun. Mag.* **54**(5), 36–42 (2016)
4. Mehta, D., Ganguly, B.: Effect of platform dynamics on aerial layer network performance. In: IEEE Military Communications Conference, pp. 1704–1709 (2014)
5. Schug, T., Dee, C., Harshman, N., et al.: Air force aerial layer networking transformation initiatives. In: IEEE Military Communications Conference, pp. 1974–1978 (2012)
6. Zhou, W.L.: Design and optimization of multiple access protocol based on environment adaptation in directional aviation relay network. Northwestern Polytechnical University, Xi'an (2021)
7. Zhou, W., Li, B., Yan, Z., Yang, M.: A combined routing path and node importance network invulnerability evaluating method for ad hoc network. In: Deng, D.-J., Pang, A.-C., Lin, C.-C. (eds.) *WiCON 2019. LNICST*, vol. 317, pp. 20–33. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-52988-8_3
8. Zhou, W., Li, B., Yan, Z., Yang, M.: A data scheduling algorithm based on link distance in directional aviation relay network. In: Lin, Y.-B., Deng, D.-J. (eds.) *SGIoT 2020. LNICST*, vol. 354, pp. 426–440. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-69514-9_33
9. Xiafei, B., Xinru, M., Ru, D.: Flying LTE for UAV dynamic access control. In: IEEE/CIC International Conference on Communications in China (ICCC), pp. 9–11 (2020)
10. Sohail, M., Leow, C., Won, S.: Non-orthogonal multiple access for unmanned aerial vehicle assisted communication. *IEEE Access* **6**, 22716–22727 (2018)
11. Jiangbin, L., Yong, Z., Zhang, R.: Cyclical multiple access in UAV-aided communications: a throughput-delay tradeoff. *IEEE Wireless Commun. Lett.* **5**(6), 600–603 (2016)
12. Bennett, D., Brown, T.: Optimal data scheduling of mobile clients serviced using beamforming antennas. In: IEEE Military Communications Conference, pp. 1–10 (2012)
13. Li, J., Han, Y.: optimal resource allocation for packet delay minimization in multi-layer UAV networks. *IEEE Commun. Lett.* **21**(3), 580–583 (2017)
14. Yang, A., Li, B., Yang, M., Yan, Z.: A bi-directional carrier sense collision avoidance neighbor discovery algorithm in directional wireless ad hoc sensor networks. *Sensors* **19**(9), 2120 (2019)