A Data Scheduling Algorithm Based on Link Distance in Directional Aviation Relay Network

Weiling Zhou, Bo Li, Zhongjiang Yan(✉), and Mao Yang

School of Electronics and Information, Northwestern Polytechnical University, Xi'an, China
2018261692@mail.nwpu.edu.cn, {libo.npu,zhjyan,yangmao}@nwpu.edu.cn

Abstract. A data scheduling algorithm based on link distance is proposed in this paper, aiming at the problem of low data transmission throughput caused by the unequal link distance between aircraft relay nodes and ground nodes in a directional aviation relay network. Firstly, the aircraft node acquires the data transmission request of the ground node during the data transmission request collection stage, and measures the transmission distance and the data transmission delay with the ground node. Secondly, a data scheduling algorithm based on downlink first uplink, long distance first and short distance is designed, which fully utilizes the communication delay expansion gain brought by the unequal link distance. Finally, the simulation results show that when the network traffic is saturated, compared with the distributed scheduling (DS) algorithm, the algorithm named link distance data scheduling (LDDS) proposed in this paper improves the network throughput by 7.4%.

Keywords: Data scheduling algorithm · Unequal link distance · Directional aviation relay network

1 Introduction

The communication network composed of pure ground nodes will cause multi-hop routing to complete the information exchange due to factors such as the ground environment occlusion and the small communication range of the node itself [1]. At this time, there is the problem of complex network topology and poor anti-destructive performance. The directional aviation relay network is a network where a ground node communicates, and it is reasonable to deploy an air node at a higher position in the central area of the network that can be line-of-sight with the ground node [2]. Let this air node relay information for the distant ground node. Among them, the directional transmission method adopted by the air node only receives and sends electromagnetic waves in a specific direction, which can increase the effective utilization of radiated power, increase confidentiality, and at the same time enhance the signal strength and increase the anti-interference

Y.-B. Lin and D.-J. Deng (Eds.): SGIoT 2020, LNICST 354, pp. 426–440, 2021.
https://doi.org/10.1007/978-3-030-69514-9_33

ability [3,4]. However, in the directional aviation relay network, as the number of ground nodes in the network increases, the problem of low data transmission efficiency due to the difference in the link distance between the ground node and the air node will be particularly prominent.

The unequal link distance means that there are multiple ground nodes in the directional working beam of the air node, and the line-of-sight distance between each ground node and the air node is unequal, resulting in unequal data propagation delay. At this time, the communication sequence of air nodes will significantly affect the overall communication efficiency of the network. The reason for the unequal link distance is the wide distribution range of ground nodes, the large number and the long distance between nodes [5,6]. In the traditional TDMA mode, the length of each time slot is the same [7]. At this time, the length of the time slot will be determined by the maximum time extension and a lot of time is wasted on the close-range nodes. For example, in a circular communication area with a radius of 300 km, the air node is located at 3 km above the center of the circle, and the distance between the two ground nodes at 30 km and 150 km from the center of the circle and the air node are: 30.15 km and 154.43 km. The one-way signal propagation delay brought by the link is: 0.1 ms and 0.515 ms respectively. The length of the transmission slot will be set to 0.515 ms, and the nearest node only needs 0.1 ms to complete the transmission, and 0.415 ms of time is wasted, resulting in a lower data transmission efficiency of the node. The same time wasted in underwater acoustic communication. The typical propagation rate of sound waves near the sea surface is 1.52 km/s, and the propagation delay caused by the reduction of the propagation rate increases [8–10].

In a wider communication area, because the distance between the air node and the ground node is very large, that is, about hundreds of kilometers, the propagation time of the wireless signal is close to the data transmission time. Studying a data scheduling algorithm makes it necessary to reasonably arrange the order of interaction between air nodes and ground nodes to reduce the delay of the entire network due to distance transmission without controlling packet collisions.

Therefore, this paper proposes a data scheduling algorithm based on unequal link distance named LDDS in directional aviation relay networks. The basic idea of the LDDS algorithm is that the air relay node collects the service requirements from the ground nodes, and combines the link distance with each ground node to reasonably integrate the uplink and downlink transmissions, and calculates the packet sending time of each node in the uplink and downlink stages. This data scheduling algorithm can shorten data transmission time and improve network transmission efficiency.

This article will first introduce the system model, introduce the communication protocol description and link inequality problems used by the network, and then specifically talk about LDDS, the newly proposed data scheduling algorithm based on link distance. Finally, the LDDS algorithm and the comparison algorithm are used to compare the simulation performance and analyze the results.

2 System Model

In a directional aviation relay network, an aircraft node relays data packets for ground nodes, which can greatly reduce the multi-hop transmission time between ground nodes. In this network, the ground nodes are stationary and evenly distributed in the circular communication area with the aircraft node as the center (the aircraft node height is H) and the network coverage radius R. Moreover, all ground nodes can reach the air node in a single hop. The clocks of all nodes are synchronized, and the directional beam of the air node rotating in all directions is divided into B beams. The communication distance of air nodes is D_{Air} ($D_{Air} > R$), and the communication distance of ground nodes is D_{Ground} ($D_{Ground} < D_{Air}$), as shown in Fig. 1.

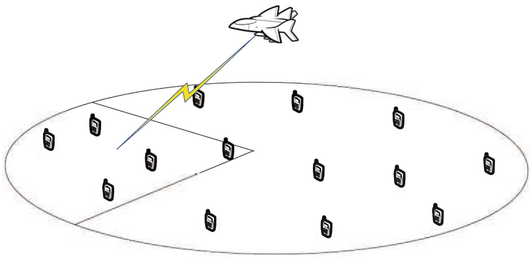

Fig. 1. Directional aviation relay network

2.1 Communication Protocol Description

The air-to-ground MAC time frame is divided into three stages, as shown in Fig. 2:

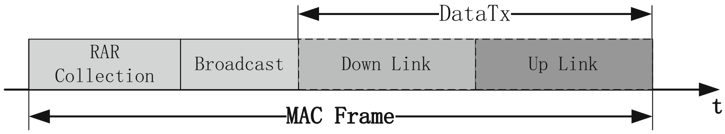

Fig. 2. MAC frame

RAR collection phase: The aircraft node and the ground node exchange data transmission requests in a Trigger-Response (Trg-Res) manner, as shown in Fig. 3. Downlink service: The aircraft node informs some ground nodes in the Trg frame that the downlink service is about to be sent. After being informed by the Trg frame that the ground node receives the Trg frame, it responds to the Res frame and prepares to receive the downlink service. Uplink service: If the ground node has uplink service that needs to be sent to the aircraft node, regardless of whether the node is included in the Trg frame, the Res frame is immediately answered after receiving the Trg frame. And in the Res frame, the local node's uplink service request is sent to the aircraft node.

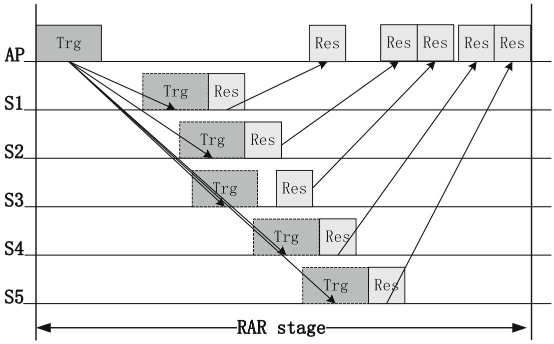

Fig. 3. RAR collection stage

Broadcast stage: After the aircraft node receives all the uplink and downlink service transmission requests, it allocates resources and broadcasts the results of the resource allocation to all nodes in the network, as shown in Fig. 4. The aircraft node sends the broadcast data packets routed by this node to the ground node, and allocates time slots for the broadcast data packets routed by the ground node.

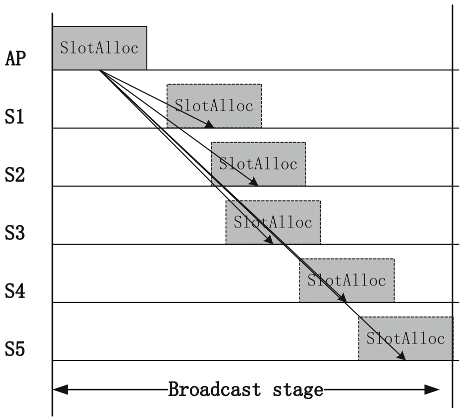

Fig. 4. Broadcast stage

Data stage: According to the result of the resource allocation algorithm, the data transmission between the aircraft node and the ground node is completed.

The duration of the uplink and downlink is dynamically adjusted according to the business situation.

The data scheduling algorithm based on link distance proposed in this paper works between the RAR collection stage and the Broadcast stage. First of all, through Trg-Res information interaction, we can know the service requirements of various nodes and the transmission delay to reach the air nodes (also the link distance of the reaction). The two pieces of information are used as the input parameters of the data scheduling algorithm. After the algorithm calculation, the resource allocation results are arranged for each ground node, and then the results are broadcast to each ground node in the Broadcast stage.

2.2 Unequal Link Distance

In the directional working beam area of the air node, the line-of-sight between each ground node and the air node is different, resulting in different transmission delays. Arrange the data transmission sequence reasonably, and use the unequal link distance to shorten the overall network delay and increase network throughput. Suppose there is two ground nodes i and j in the current working area of aerial node a, where node i is closer to aerial node a than node j. The total traffic in the network (including uplink and downlink services) is B_{UpLink}. Data transmission consumes time is T_{Data}. Then the throughput of the network is $W_{ThroughPut}$:

$$W_{ThroughPut} = \frac{B_{UpLink}}{T_{Data}} \tag{1}$$

When the network traffic is constant, the shorter the transmission time required, the higher the unit throughput of the network. At the same time, the following three constraints must be met:

* Conditions where the STA's uplink and downlink working time periods cannot conflict (for a single STA node). Use T^{Up}_{Start} and T^{Down}_{Start} to represent the start time of the uplink and downlink. Use T^{Up}_{End} and T^{Down}_{End} to represent the end time of the uplink and downlink. Time needs to satisfy:

$$\begin{cases} (T^{Up}_{Start} > T^{Down}_{Start}) and (T^{Up}_{End} > T^{Down}_{End}) \\ (T^{Down}_{Start} > T^{Up}_{Start}) and (T^{Down}_{End} > T^{Up}_{End}) \end{cases} \tag{2}$$

* The condition for the AP to receive packets uplink does not conflict is that no data collision can occur during signal transmission. The packet sending time of node i is T^{Data}_i, business demand is B_i. The packet sending time of node j is T^{Data}_j, business demand is B_j. And the data transmission rate of all nodes is the same as v_{Data}. The link distance between node a and node i is d_{ai}. The link distance between node a and node j is d_{aj}.

$$T^{Data}_i + \frac{B_i}{v_{Data}} + \frac{d_{ai}}{c} \geq T^{Data}_j + \frac{d_{aj}}{c} \tag{3}$$

* AP and STA can finish the business within the designated time slot.

3 Data Scheduling Algorithm Based on Link Distance

The core idea of LDDS algorithm used in directional aviation relay network:

The downlink has higher scheduling priority than the uplink: In a directional aviation relay network, the main role of an aircraft node is an air relay node, that is, an aircraft node is generally not a source node or a destination node of data. Therefore, the algorithm adopts the principle of prioritizing downlink data transmission. In this way, if the downlink data can be transmitted preferentially, the storage unit at the aircraft node can be released first, and then it is convenient to store the uplink data information newly sent by the ground node.

The long-distance link traffic has higher scheduling priority than the short-distance link: From the perspective of time slot allocation based on link distance, during downlink data transmission, if the aircraft node preferentially sends data to the long-distance node, it can opportunistically send data to close nodes within the time slot for the long-distance node to reply. Thereby improving the time slot utilization rate and the efficiency of the multiple access protocol.

3.1 Overall Algorithm Design

The directional aviation relay network is a single-AP multi-STA network. Due to the existence of a central control node in the network, it is possible to statistically analyze the uplink data request carried by the response from the air node (hereinafter referred to as AP). The transmission arrangement is obtained through a scheduling algorithm, and this time slot arrangement is sent to all ground nodes (hereinafter referred to as STAs) through broadcast control packets.

In order to make efficient use of time resources, the data scheduling algorithm proposed in this paper will obscure the uplink and downlink data transmission stages of the entire network in the general protocol flow. Instead, it is considered from the AP node, so that the AP can be continuously down and up as much as possible, as shown in the Fig. 5.

When the uplink and downlink services are symmetrical, this algorithm will not overlap the packet sending and receiving times at the STA node. But for a more general situation: when the uplink and downlink services are asymmetric, there may be overlap of uplink and downlink working hours at the STA, and further adjustment and optimization are needed. The general flow of this scheduling algorithm is as follows:

- step 1 Based on the start time T_{Base}^{Start} of the AP sending packets to the farthest STA, first calculate the subsequent relative time;
- step 2 Using the downlink algorithm mentioned in Sect. 3.3, calculate the AP's packet sending schedule for each STA, and in this case the STA's packet receiving schedule;
- step 3 Use the uplink algorithm mentioned in Sect. 3.2 to calculate the timetable for each STA to send packets to the AP, and in this case, the AP's timetable for receiving packets corresponding to the data of each STA;

step 4 According to the link distance, the working area of each STA is detected sequentially from far to near, and whether there is an overlap of uplink and downlink working time. If there is overlap, go to step 5, otherwise go to step 6;

step 5 Advance the AP's packet sending time to the min (packet sending schedule) it maintains, and synchronously modify the AP packet sending schedule;

step 6 If the packet sending schedule has been modified, need to skip back to step 4 and check again whether there is any overlap in the working area of each STA.

step 7 After the collision detection is completed, the true packet sending time of AP and STA is re-determined by the following formula:

$$T_{Real}^{Start} = min(min(APtimetable), min(STAtimetable)) \tag{4}$$

The data transmission stage calculated at the end of the algorithm flow is shown in Fig. 5:

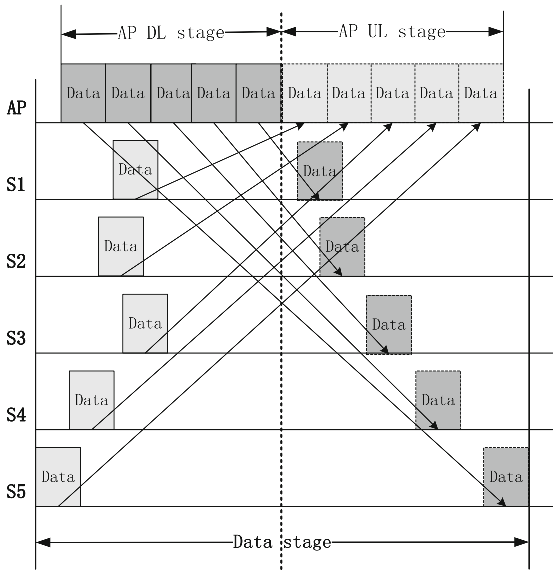

Fig. 5. Data transmission stage

3.2 Uplink Algorithm Design

In order to make the receiving end of the uplink data get the maximum throughput within a certain period of time, the best way is to arrange the sending time of each STA reasonably, so that the AP can continuously receive and process data without gaps, as shown in the Fig. 6:

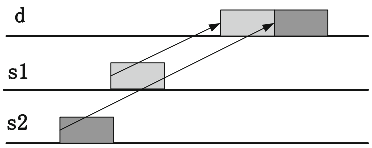

Fig. 6. Schematic diagram of AP receiving package

In the RAR stage, each STA writes its own data uplink request in the Res control packet and sends it to the AP. The AP end can calculate and know the transmission delay between each STA and the AP from the sending timestamp of Res and the current time. The data length of the data request carried by Res and the predetermined data transmission rate determine the data transmission duration. Figure 7 shows the uplink scheduling arrangement of the LDDS algorithm.

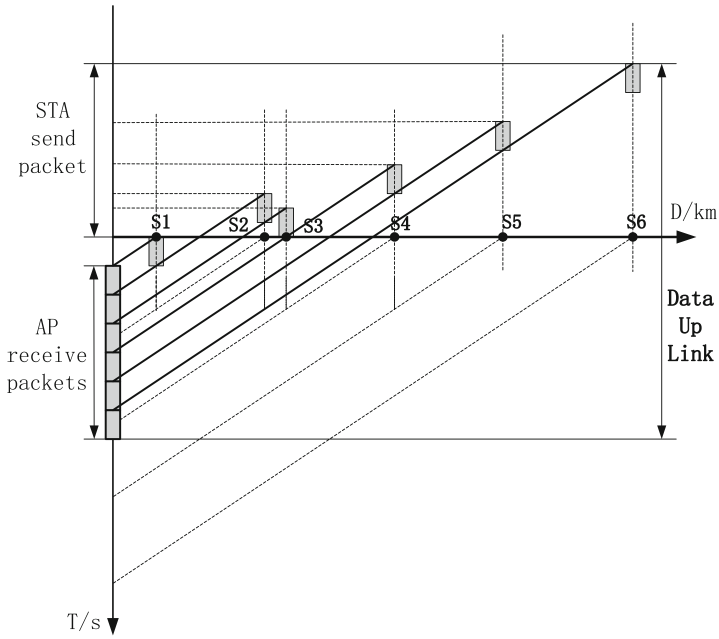

Fig. 7. Uplink algorithm diagram

In order of increasing transmission delay ($D_{S_1d} < D_{S_2d} < ... < D_{S_nd}$), the following data information table is organized: (Where N is the total number of STAs in the current network, and n is the number of STAs in the current AP's working sector).

The input parameters of this algorithm are: the service request of each STA. Under the condition that the data transmission rate is known, it is equivalent to the data transmission time $L_{Ul_i}^{data}(1 \le i \le n)$, transmission delay $D_{S_i d}(1 \le i \le n)$, and the beginning of the data uplink phase is T_{start}. Calculate and output the packet sending time $T_k^{data}(1 \le k \le n)$ of each STA.

The algorithm flow is as follows: Firstly, the data sent from the closest STA node S_1 is set to the time when the AP starts to work. Assuming that T_1^{data} is a certain constant, then the start time of receiving the first packet is:

$$T_1^{data} + D_{S_1 d} \tag{5}$$

The start time of receiving the second packet:

$$T_1^{data} + D_{S_1 d} + L_1^{data} \tag{6}$$

...

Start time of receiving the i-th packet:

$$T_1^{data} + D_{S_1 d} + \sum_{j=1}^{i-1} L_j^{data}(2 \le i \le n) \tag{7}$$

According to each packet receiving time and transmission delay table, the packet sending time of each STA is reversed:

$$\begin{cases} T_1^{data} \\ T_2^{data} = T_1^{data} + D_{S_1 d} + L_1^{data} - D_{S_2 d} \\ \cdots \\ T_k^{data} = T_1^{data} + D_{S_1 d} + \sum_{j=1}^{k-1} L_j^{data} - D_{S_k d}(2 \le k \le n) \end{cases} \tag{8}$$

From the above formula, it is found that the packet sending time $T_k^{data}(1 \le k \le n)$ of each STA is a certain value and is directly related to the value of T_1^{data}. The starting time of the data uplink phase is the known data. T_{Start}^{Ul}

$$min(T_k^{data}(1 \le k \le n)) = T_{Start}^{Ul} \tag{9}$$

From the above formula, T_1^{data} can be solved, so that $T_k^{data}(1 \le k \le n)$ can be solved, so that the packet sending time of all STAs can be obtained.

3.3 Downlink Algorithm Design

In the downlink data transmission phase, the air AP node sends data packets to the ground STA node. In the downlink data transmission, if the aircraft node preferentially sends data to the long-distance node, it can opportunistically send data to the short-distance node within the time gap waiting for the long-distance node to reply. In this way, the time slot utilization rate and the efficiency of the multiple access protocol can be improved. Figure 8 shows the downlink scheduling arrangement of the LDDS algorithm.

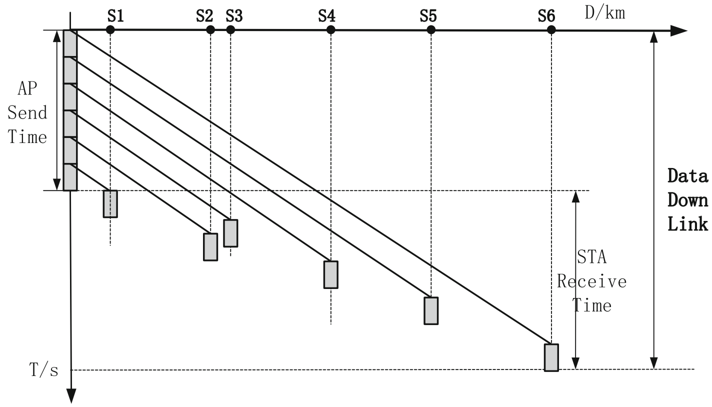

Fig. 8. Downlink algorithm diagram

Start time of the downlink phase: (T_{BEnd} is the end time of the broadcast phase of the current time frame):

$$T^{Dl}_{Start} = T_{BEnd} \tag{10}$$

The data information table maintained by the AP node itself records the service transmission requirements of the AP for each STA. Then, according to the data transmission rate v_{data}, the transmission duration $L^{data}_{Dl_i}$ of the downlink transmission data, the transmission delay D_{S_id} obtained from the RAR stage, and the strategy of giving priority to the transmission of the remote STA can calculate the packet sending time of the AP to each STA:

$$\begin{cases} T^{data}_1 = T^{Dl}_{Start} \\ T^{data}_2 = T^{data}_1 + L^{data}_{Dl_1} \\ \dots \\ T^{data}_k = T^{data}_1 + \sum_{j=1}^{k-1} L^{data}_{Dl_j} (2 \leq k \leq n) \end{cases} \tag{11}$$

And calculate the duration of the shortest downlink phase that can get the network:

$$L^{data}_{Dl} = max(T^{data}_1 + D_{S_1d} + L^{data}_{Dl_1}, ..., T^{data}_n + D_{S_nd} + L^{data}_{Dl_n}) \tag{12}$$

For AP, its uplink end time is its downlink start time, and the two phases will work without interruption.

4 Simulation and Results

At present, the simulation of wireless communication systems is generally divided into two categories: link-level simulation and system-level simulation. Among them, the link-level simulation mainly focuses on the performance of wireless channel and physical layer algorithms, and the signal-to-noise ratio error rate is used as the judging standard; while the system-level simulation will focus on the impact of high-level protocols and network topology on network performance. The signal delay is used as the criterion. In order to accurately express the overall performance of the data scheduling algorithm proposed in this paper, we choose to perform verification analysis on the link-level and system-level integrated simulation platform based on NS3.

A distributed scheduling (DS algorithm) is proposed [8]. In this algorithm, in the data downlink phase, the AP sends packets to the STA in order from far to near. Then wait for all STAs to enter the uplink phase after receiving packets. All STAs send packets at the beginning of the uplink. If it is predicted that there will be a collision at the AP end when receiving packets, the remote node in the conflicting STA will postpone the packet.

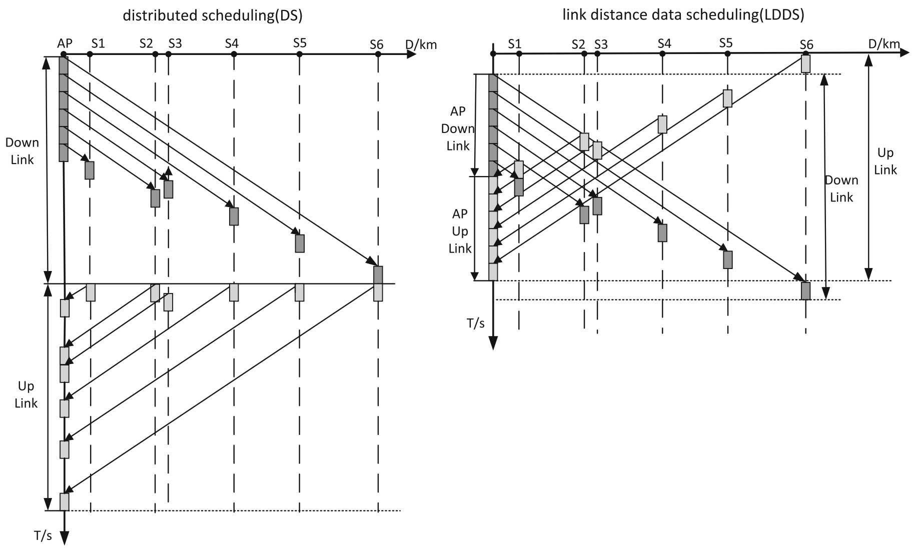

Fig. 9. DS and LDDS scheduling algorithms

Figure 9 represent the principles of DS and LDDS scheduling algorithms. T_{Data} represents the total time required for the transmission of all services on the network; T_{trans} represents the propagation delay caused by the maximum link distance in the network; $T^{'}_{Data}$ is the length of time required to represent the traffic transmission of a single node (in this analysis, set all nodes to have the same uplink and downlink traffic).

Test scenario: Design a directional aviation relay network so that 128 communication nodes are located in a circular area with a radius of 300 km. The only air node is 3 km above the center of the circle, and the remaining 127 ground nodes are evenly and randomly distributed inside the circle. The air nodes use directional beam communication, which is divided into 16 hemispherical coverage beams. An air node can reach any ground node in the circular communication area in a single hop. The size of a single data packet is $256B$, the data transmission rate is 54 Mbps, all nodes are stationary and the clocks are synchronized. Test the performance of various networks that communicate with each other through the assistance of air node relay forwarding between ground nodes.

Let the air node be a node relay node of the ground area in a directional beam, and for a circular uniformly distributed network, the number of ground nodes near the circular air node is less, and the number of ground nodes closer to the edge of the network is greater. Therefore, in the working beam of the AP node, there are 8 ground nodes on average and the distribution form relative to the AP is from sparse to dense. Under this scenario, simulation test was conducted to verify the performance characteristics of LDDS algorithm and DS algorithm.

In the case of network transmission of the same traffic, the time-consuming situation of the two algorithms is shown in Table 1.

Table 1. Algorithm time-consuming comparison

Business volume	DS time consuming	LDDS time consuming	LDDS saves time
$T_{Data} < T_{trans}$	$2T_{trans} + 2T'_{Data}$	$2T_{trans} - T_{Data} + T'_{Data}$	$T_{Data} + T'_{Data}$
$T_{Data} = T_{trans}$	$2T_{trans} + 2T'_{Data}$	$T_{trans} + T'_{Data}$	$T_{Data} + T'_{Data}$
$T_{Data} > T_{trans}$	$2T_{Data} + 2T'_{Data}$	T_{Data}	$2T'_{Data}$

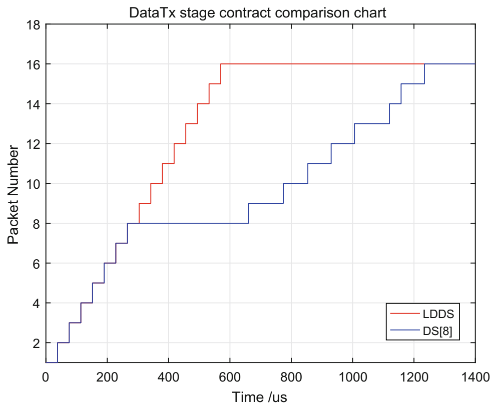

Fig. 10. The number of packets sent in a single Data phase varies with time

The x-axis of Fig. 10 is the time-consuming situation of the algorithm, and the y-axis is the number of packets sent (all nodes send a unit-length data packet).

It can be seen from the figure that the performance of the two algorithms is the same in the initial AP downlink phase; but in the AP uplink phase, the time required by the new algorithm is significantly better than the comparison algorithm. This is because after the LDDS algorithm enters the Data transmission phase, the STA will prepare to send packets uplink. In the DS algorithm, the uplink and downlink are completely separated. The STA must wait for the AP to complete the downlink phase before it can start the uplink transmission. This will cause all the packets to be sent or are in the link transmission state during the start of the uplink phase, and the AP will have a period of idle time, resulting in a waste of time. The LDDS algorithm proposed in this paper makes good use of link inequality information to arrange STA to send packets in advance, avoiding the time resource consumption of AP here.

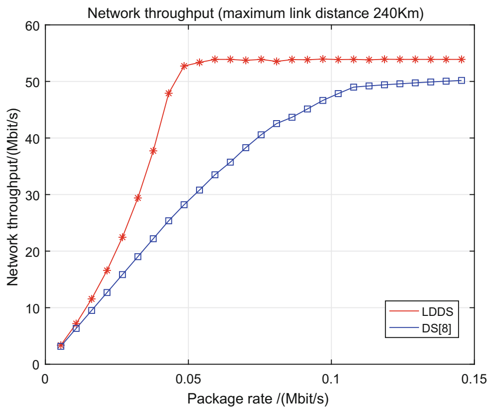

Fig. 11. Network throughput changes with the rate of production packets

The x-axis of Fig. 11 is the packet production rate, and the y-axis is the network throughput (the maximum link distance in this test scenario is 240 km). It can be seen from the figure that the LDDS algorithm can reach the saturation point of network throughput faster than the LDDS algorithm. It is easy to see through the principle analysis table of the LDDS algorithm and the DS algorithm. When the maximum link distance of the network is consistent with the transmission time required for the network data, the LDDS algorithm will have the most obvious throughput gain compared to the DS algorithm, and also reach the maximum throughput of the network. When the network traffic is saturated, compared with the DS algorithm, the network throughput is improved by 7.4%

The x-axis of Fig. 12 is the maximum link distance in the network, and the y-axis is the network throughput. Under the condition that the total traffic to be transmitted by the network is fixed, when the distance between the links in the network is small, the LDDS algorithm transmits all the services in one time, which is roughly equal to the service transmission time, and there is no

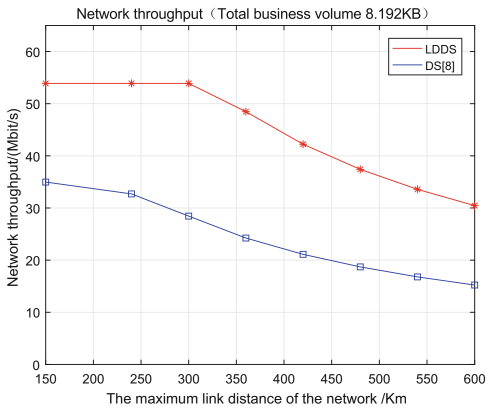

Fig. 12. Network throughput changes with the rate of production packets

additional link propagation delay. Will get the maximum network throughput. When the distance between the links in the network is large, the LDDS algorithm will increase the time it takes to transmit network services and the DS algorithm will increase the long-distance propagation cost. However, the total time consumption of the LDDS algorithm will always be less than that of the DS algorithm, so the network throughput of the LDDS algorithm is always better than the DS algorithm.

5 Conclusion

A data scheduling algorithm based on link distance is proposed in the directional aviation relay network, which blurs the uplink and downlink stages of the overall network, and keeps the relay nodes in working state as much as possible. Therefore, the air nodes and the ground nodes can communicate efficiently, improve the utilization rate of network resources, and increase the network throughput. And through simulation tests, verification shows that using this data scheduling algorithm in directional aviation relay networks, the network will have better throughput.

Acknowledgement. This work was supported in part by Science and Technology on Avionics Integration Laboratory and the Aeronautical Science Foundation of China (Grant No. 201955053002), the National Natural Science Foundations of CHINA (Grant No. 61871322, No. 61771392, No. 61771390, and No. 61501373), and Science and Technology on Avionics Integration Laboratory and the Aeronautical Science Foundation of China (Grant No. 20185553035).

References

1. Xu, Z., Yuan, J., et al.: Multi-UAV relay network supporting mobile ad hoc network communication. J. Tsinghua Univ. (Nat. Sci. Ed.) **51**(2), 8–13 (2011)

2. Yan, Z., Li, Q., Li, B., Yang, M.: A multiple access protocol based on link distance and ring splitting in directional aviation relay network. J. Northwestern Polytechnical Univ. **38**(1), 147–154 (2020)
3. Jing, Z., Zeng, H., Li, D.: Research on MAC networking technology of directional ad hoc network. Communication technology, pp. 1041–1047 (2014)
4. Macleod, R.B., Margetts, A.: Networked airborne communications using adaptive multi-beam directional links. In: 2016 IEEE Aerospace Conference (2016)
5. Liang, L.: Node design of self-organizing long-distance wireless communication system. Ph.D. thesis, North University of China (2011)
6. Lou, H.P., Sun, Y.Q., Fan, G.: Application of long-distance wireless communication technologies in supervisory control system. J. Sci-Tech Inf. Dev. Econ. **16**(17), 235–237 (2006)
7. Mo, P., Li, S.: TDMA time slot allocation algorithm research and Qt platform implementation (2017)
8. Zhang, J., Lai, H., Xiong, Y.: Concurrent transmission based on distributed scheduling for underwater acoustic networks. Sensors **19**, 1871 (2019)
9. Miguel-Angel, L.N., Jose-Miguel, M.R., Pablo, O., Javier, P.: Optimal scheduling and fair service policy for STDMA in underwater networks with acoustic communications. Sensors **18**(2), 612 (2018)
10. Hu, T., Fei, Y.: DSH-MAC: medium access control based on decoupled and suppressed handshaking for long-delay underwater acoustic sensor networks. In: 2013 IEEE 38th Conference on Local Computer Networks (LCN 2013) (2013)