A New MAC Protocol for Intra-flight Data Link Based on Directional Antenna

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Abstract. Based on directional antenna, the capability of the intra-flight data link such as anti-jamming and low interception can be greatly improved. However, it also brings some problems: obtaining the destination node location information, meeting the real-time requirement of the burst traffic and sharing situation information with directional antenna, etc. To solve the problems, DP-CLMA (Dynamic Priority-Chain Link Multiple Access) protocol based on directional antenna is proposed, and some corresponding mechanisms are described in detail. By analyzing time delay performance of DP-CLMA protocol, the results show that DP-CLMA protocol adapts to intra-flight tactical data transmission.

1. Introduction

The intra-flight data link is a new dedicated tactical data link used in the formation for U.S. military [1] [2]. Its main function is to meet the high-speed, secure and reliable information sharing between the planes, and sequentially improve the cooperative engagement capability (CEC) of the formation.

With the improvement of reconnaissance technology, the probability of tactical information being jammed and intercepted in air combat has increased greatly [3]. It requires that intra-flight data link must have excellent capability of anti-jamming and low interception. The traditional methods mainly rely on power control, spread spectrum technology and frequency hopping technology, etc, and most of the traditional methods are based on omnidirectional antenna. With the development of antenna technology, research of intra-flight data link based on directional antenna has become popular in recent years. Presently, U.S. Air Force has applied directional antenna successfully to the IFDL in F-22 and the MADL in F-35 [4]-[7].

The main research work of this paper is aimed at the multiple access protocol for intra-flight data link based on directional antenna. The remainder of this paper is structured as follows. Section II presents some problems when using directional antenna in intra-flight data link. Section III presents the DP-CLMA protocol of intra-flight data link and proposed relevant protocol mechanisms, followed by simulations and analysis of the time delay performance in Section IV. Section V concludes the paper.

2. Difficult problems when using directional antenna

By using the directional antenna, the spatial reuse efficiency will be greatly improved and the network capacity will be largely increased [8] [9], but it also brings some problems.
2.1 Obtaining the Destination Node Location Information
To create a directional communication between nodes with directional antenna, the source node must acquire the location of destination node in advance, and then forms a directional narrow beam pointing to the destination node.

2.2 Meeting the Real-time Requirement of the Burst Traffic
Information transmitted in intra-flight data link includes not only situation information, but also some burst information, such as guidance handover information, alarm information, etc, which often have higher real-time requirement. The time sensitivity of air combat is below the second-grade [1], when the burst information is generated, the source node must transmit it to the destination node quickly to ensure its real-time requirement with directional antenna.

2.3 Sharing Situation Information with Directional Antenna
One of the main functions of intra-flight data link is to share situation information among all the aircrafts in the formation. Information sharing can be achieved through broadcasting with omnidirectional antenna, but for the directional antenna, we need to design a new sharing mechanism.

3. DP-CLMA protocol based on directional antenna
Recently, the multiple access protocol for Ad Hoc network based on directional antenna has been deeply studied, most of which are based on the RTS/CTS reservation mechanism. There are 3 types of combination in RTS/CTS reservation mechanism: omnidirectional RTS(ORTS) - omnidirectional CTS(OCTS), directional RTS(DRTS) - omnidirectional CTS, directional RTS - directional CTS(DCTS) [10].

DP-CLMA is based on CSMA/CA [11][12] and ORTS/OCTS mechanism [10]. When a node needs to send a message, monitors the state of the channel firstly. If it is idle, the node sends the ORTS to make a reservation, and the destination node sends the OCTS after receiving the ORTS successfully. When the source node receives the OCTS from the destination node, it means the reservation success. In DP-CLMA, a node can only communicate with one node with directional antenna at the same time. The distance between nodes in the formation does not exceed 20km.

There are three mechanisms to solve these problems in DP-CLMA, and they will be expatiated in the following.

3.1 Location Information contained in the Control Packet
DP-CLMA solves the problem of obtaining the destination node location information by adding the location information to the ORTS and the OCTS control packet. Reference [10] points out that a node can effectively monitor the state of the communication channel only when the duration for transmitting control packet is longer than the duration that the control packet travels in the air. If the information transmission rate is 2Mbps, the minimum length of control packet is $6.67 \times 10^3 \times 2 \times 10^6 = 133.4$ bits.

DP-CLMA provides that the length of the ORTS is 260 bits, the OCTS is 244 bits, and the ACK is 144bits. Frame format of the ORTS/OCTS is shown in Figure 1. In the ORTS, the fields of RA and TA contain information of MAC (Media Access Control) address of the destination node and the source node respectively. In the OCTS, the field of RA is the copy of TA in the ORTS frame. The field of Location of the sending node contains location information.
3.2 Chain Link Model for Situation Information Sharing

Situation information is transmitted in the formation with confirmed order and interval time $t$ with directional antenna, just like all the aircrafts are linked by a chain.

![Figure 2. Sketch map of chain link situation information sharing mechanism](image)

As shown in Figure 2, node 1–8 represent aircrafts (No.1–8) in the formation. Node 1 transmits its situation information to node 2 with directional antenna, after an interval time $t$, node 2 transmits situation information of node 1 and its own to node 3, following progress continues in the same way. When node 8 completes the directional communication with node 1, node 1 gets situation information of all the other nodes. Interval time $t$ will be confirmed in the Following.

It is supposed that airborne intelligent antenna can only forms one directional beam at a time, and situation information is transmitted in the formation with confirmed order and interval time $t$. As a result, situation information of node 1 that received by node 8 is not in real time. In order to meet real-time requirement of air combat, situation information updating period should not be too long. Reference [4] points out that the rotate speed of the early warning radar on E-3 is $6r/min$, that is to say situation information updates every 10 seconds. Considering that situation changes rapidly in air combat, DP-CLMA provides that the maximum updating period $T_{\text{max}}$ of situation information is 5 seconds. When the number of aircrafts in the formation is $M$, the interval time $t$ to transmit situation information in the network is $t = \frac{5}{(M-1)}$.

3.3 Back-off Mechanism with Dynamic Priority

DP-CLMA is based on CSMA/CA and ORTS/OCTS, a node needs to contend with other nodes to occupy the communication channel. If fails, it is believed that the collision has happened, and all the nodes which have encountered a collision need to back-off to avoid collision in the next competition. If succeeds, data will be transmitted and the node will wait for the ACK with directional antenna.

3.3.1 Directional Network Allocation Vector

Each node has several counters, these counters represent different other nodes in the network. When a node needs to make a reservation with another node, it must confirm that the channel is idle and the value of the counter which represents the destination node is zero. Only under these two conditions can a node make a reservation with another. In Figure 1, the field of Duration contains Directional Network
Allocation Vector \( i(dNAV_i) \) information. The node updates the value of the counter which represent node \( i \) according to the \( dNAV_i \) information received.

### 3.3.2. The Time of Starting to Contend for Transmitting Situation Information

To ensure that situation information update period be less than 5 seconds, DP-CLMA provides the time of starting to contend for transmitting situation information. As shown detailed in Figure 3, there are \( M \) nodes in the formation, corresponding nodes begin to contend for transmitting situation information at the time of \( T_0 \sim T_{n-1} \). If fails, the priority of situation information will be improved to the second, thus the node will transmit the information to next node before \( T_0 + (i-1) \times \lceil 5/(M-1) \rceil \) (\( i \) being the node number, \( M \) the number of network members), otherwise the update period will longer than 5 seconds. The time of \( T_0 \sim T_{n-1} \) is not equal to the time of \( T_0 + (i-1) \times \lceil 5/(M-1) \rceil \). \( T_0 \sim T_{n-1} \) is the time that nodes begin to contend, while \( T_0 + (i-1) \times \lceil 5/(M-1) \rceil \) is the dead line time that a nodes transmits situation information to the next node.

![Figure 3. Sketch map of frame format in a](image)

### 3.3.3 Magnitude of the Contention Window (CW)

In DP-CLMA, guidance handover information and alarm information are provided with the highest priority; command control (C\(^2\)) information and situation information which failed in the first contention are provided with the second priority; situation information which is the first time to contend is provided with the third priority. Magnitude of the contention window with different priorities is different.

As shown in Figure 4, DP-CLMA provides that the minimum contention window (\( CW_{\text{min}} \)) of the first priority information is equal to its maximum contention window (\( CW_{\text{max}} \)), \( CW_{\text{min}} = CW_{\text{max}} = 23-1=7 \); \( CW_{\text{min}} \) of the second priority information is 15, \( CW_{\text{max}} \) is 63; and the original contention window (\( CW_{\text{o}} \)) of the third priority information is 127. A node retry to contend can not exceed 8 times. To ensure that important data in intra-flight data link won’t be lost when a node retry exceeds 8 times, DP-CLMA provides that the first priority information is transmitted with no limit about retry times, and the second priority information that exceeds the maximum retry times should be transmitted unlimited with the probability of 0.6, while it should be dropped with the probability of 0.4.
4. Time delay performance analysis

In the simulation, it is provided that the size of all packets is 128kbits, the distance between nodes is 20km, and the simulation time is 1 hour.

The maximum updating period of situation information is 5 seconds and the packet arrival rate is 0.2 packets/s. Guidance handover information and alarm information take a small proportion of the whole information in the formation, thus all the packet arrival rate is at low level. In the simulation, we experiment at a low packet arrival rate firstly, and then test the time delay performance with the highest priority information at higher packet arrival rate.

4.1 Different Priorities

Figure 5 is time delay performance graph of different priority when the formation nodes number is 4, and the packet arrival rate are $\lambda_1 = 1, \lambda_2 = 0.7, \lambda_3 = 0.2$ for the Figure 5(a), $\lambda_1 = 0.2, \lambda_2 = 1, \lambda_3 = 0.2$ for the Figure 5(b). $\lambda_i$ represents the packet arrival rate of the information with the priority of level $i$.

![Figure 5](image)

Figure 5. Time delay performance graph of different priority

Conclusions will be got by analyzing these figures above:

1. The average value of time delay will increase with the improvement of information priority.
2. When priority remains constant, the average value of time delay also increases with the increase of the packet arrival rate.
3. Even though the packet arrival rate of the second priority information increases to 1 packets/s, which is much higher than 0.2 packets/s (the packet arrival rate of the third priority information), the average value of time delay of the second priority information is still equivalent to that of the third priority information, about 115ms. This indicates that the priority of information plays a primary role in affecting time delay performance.
4. All the average value of time delay is below 125ms, which is able to meet the time delay requirement in intra-flight data link.

4.2 Different Packet Arrival Rate

Figure 6 ~ Figure 9 are time delay performance graphs when the packet arrival rate are respectively $\lambda = 10, \lambda = 6, \lambda = 3, \lambda = 1$, and the formation nodes number is 4.
Conclusions will be got by analyzing these figures above:

1. When $\lambda \leq 10$, the average value of time delay is below 250 ms.
2. When it reaches $\lambda \leq 3$, the reducing of the average value of time delay slows down. It shows that there is a minimum of the average value of time delay.

4.3 Different Network Nodes Number

Figure 10 and Figure 11 are time delay graphs when the formation nodes number is respectively 4 and 8, and the packet arrival rate is $\lambda = 1$. Figure 12 and Figure 13 are time delay graphs when the formation nodes number is respectively 4 and 8, and the packet arrival rate is $\lambda = 10$.

Conclusions will be got by analyzing these figures above:

1. The average value of time delay increases with the increase of the formation nodes number under the condition of the same packet arrival rate.
2. The increment of the average value of time delay caused by the increase of the formation nodes number when $\lambda = 1$ is less than the increment when $\lambda = 10$. It shows that the formation nodes number has more effects on the time delay performance when the packet arrival rate is high.

5. Conclusions

When directional antenna is being used in the multiple access protocol for intra-flight data link, data transmission between nodes won’t have effect on the reservation of other nodes, therefore, time delay is greatly reduced. The simulation results show that time delay performance of DP-CLMA protocol can meet the requirement of intra-flight data link well.

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