Research on Delay Sensitive Transmission Technology for High Dynamic Group Distribution Networking of Aerial High Dynamic Node

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Abstract. Aerial high dynamic node is the core equipment for seizing the air-control right combat, with the combat mission needs and the technological development of both attack and defence, there is an urgent need to enhance the combat effectiveness through networked combat, the communication delay of the nodes of the bomb group of the group combat is very high, the analysis of the composition of the delay of the nodes of each node within the bomb group, the design of a MAC layer based on the degree of obstruction of the optimal Dijkstra path selection mechanism, the algorithm is given to the programme. The queuing delay of nodes is effectively reduced by the optimised path selection scheme. A relay node delay guarantee mechanism based on a new type of dynamic flow token bucket is studied to solve the problem of queuing many packets at the relay node. After simulation analysis of the algorithm, the scheme is effective, can effectively improve the aerial high dynamic node network delay sensitivity.

Keywords: aerial high dynamic node · dynamic networking · time delay · sensitive transmission technology · data transmission

1 Introduction

The field of air warfare has undergone significant changes due to the rapid development of new technologies. These changes include the shift from absolute air control to relative air control, and the emergence of concepts such as 'distributed air warfare' and 'penetrating air control' [1–7]. The evolution of air battlefield combat systems has progressed from single aircraft combat to multi-aircraft mixed formation combat, and then to the distributed penetration of manned/unmanned systems. This evolution has been driven by the purpose of seizing control of the air. It is important to maintain a clear and logical structure when discussing these complex systems. The development of aerial high dynamic nodes by the world's military powers has advanced significantly. These nodes

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have evolved from being used in simple battlefield environments to being developed for complex battlefield environments [8–10]. However, this increased combat capability has come at a cost, as the price per unit has increased while the trend for performance enhancement has decreased. The effectiveness of a single bomb is approaching its limit, and further improvements are becoming increasingly difficult. To address the bottleneck, further enhancements must be achieved without incurring unacceptable costs. This can be accomplished through the use of multi-bomb high dynamic synergy, group distribution of ballistic grouping, and network thinking. Distributed synergy technology should also be utilized to make the most of available resources. The goal is to accelerate the OODA closed loop from a system perspective.

The evolution of air battlefield combat systems has progressed from single aircraft combat to multi-aircraft mixed formation combat and then to the distributed penetration of manned/unmanned systems, all driven by the need to seize control of the air. However, with the advancement of aerial high dynamic nodes, these systems now face significant challenges. As these nodes are increasingly deployed in complex battlefield environments, they encounter issues such as high transmission delays, network variability, and limited resources. To address these challenges, this paper explores the design and implementation of delay-sensitive transmission technologies that ensure low-latency communication within high-dynamic group distribution networks. Specifically, it introduces a novel MAC layer-based optimal path selection mechanism that reduces queuing delays and a dynamic flow token bucket mechanism to manage relay node congestion. Through simulation and analysis, the paper demonstrates the effectiveness of these methods in enhancing the delay sensitivity of high-dynamic node networks.

2 Analysis of Delay Composition in Highly Dynamic Node Networking for Aerial High Dynamic Nodes

This paper discusses the delay in the aerial high dynamic node swarm network, specifically the time from generation to delivery of control, guidance, and detection data. Previous research has focused on delay-sensitive networks [11–16]. In the swarm combat network, the end-to-end delay is mainly composed of the following components:

- System deviation. That is, the system time deviation between different nodes within the bomb group due to software, hardware implementation or other battlefield environment factors.
- Processing delay. That is, the length of time experienced by the data to reach the transmit queue from the receive port. Usually the processing latency of a node is at the microsecond level or lower and is relatively constant, which is negligible under the overall node-to-node latency.
- Queuing delay. That is, the length of time from the time the data enters the queue to the time the data begins the link layer access strategy. The queuing delay is related to the design of the queue, in the traditional first-in-first-out queue, the data needs to wait until the data arriving before it in the queue are sent before entering the access phase.

- Access delay. That is, the waiting time generated by the data in the bullet group network due to the multi-access protocol and back-off. When the data is ready to be sent, different MAC protocols will adopt different strategies to judge whether the data can be sent to the wireless channel at this time, and this delay is related to the design of the MAC protocol.
- Transmission delay. That is, the time experienced by the last bit of a data packet from the time it is sent to the time it reaches the destination node. The transmission delay is affected by the physical distance between the sending node and the receiving node, etc., and the greater the distance, the greater the transmission delay.

Therefore, the total delay from sending the node to receiving the node t_{total}:

$$t_{\text{total}} = t_{\text{offseet}} + t_{\text{quene}} + t_{\text{mac}} + t_{\text{prop}} + t_{\text{process}} \tag{1}$$

where t_{offset} initial system time deviation, t_{quene} queuing delay, t_{mac} access delay, t_{prop} transmission delay, t_{process} processing delay.

Figure 1 illustrates the delay composition in one-hop transmission. In the case of packet size determination, the single hop t_{prop} can be regarded as a fixed value due to the similar distance between nodes and the t_{process} is negligible, while t_{quene} is more related to the adopted strategy. Therefore, the focus is on the queuing delay sensitivity technique on the whole link and at the relay nodes, and the delay sensitivity of t_{offset} and t_{mac} is analysed in the study.

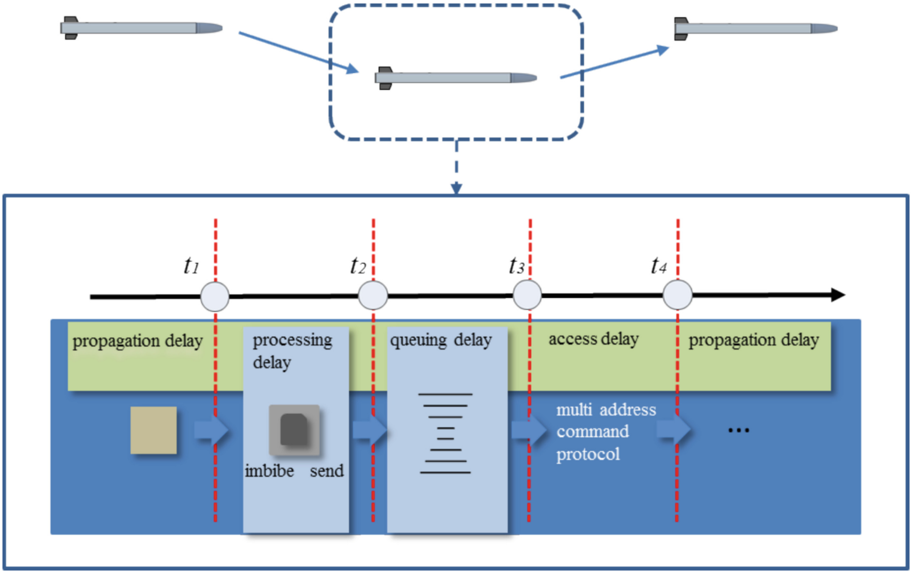

Fig. 1. Transmission delay composition of node group network

3 Bomb Group Time Synchronization Design

A uniform time logic needs to be established between groups of nodes. Under certain assumptions, there is a deviation t_{offset} in the system time between different nodes, which must be eliminated when communicating between groups of nodes.

Let Node $Node_{\mathrm{i}}$ sends packet $data_{\alpha}$ to node $Node_{\mathrm{j}}$ with local time $t_{\mathrm{data\_\alpha}}$ and $Node_{\mathrm{j}}$ receives $data_{\alpha}$ with local time $t_{\mathrm{data\_\beta}}$, $Node_{\mathrm{j}}$ sends packet $data_{\beta}$ to $Node_{\mathrm{i}}$ with local time $t_{\mathrm{data\_\gamma}}$ and the packet carries the time $t_{\mathrm{data\_\beta}}$。 $Node_{\mathrm{i}}$ receives $data_{\beta}$ and records the local time $t_{\mathrm{data\_\delta}}$ from the packet Get time $t_{\mathrm{data\_\beta}}$. Then there is:

$$\begin{cases} t_{data\_\alpha} + t_{offset} + t_{prop\_Node_i\_Node_j} = t_{data\_\beta} \\ t_{data\_\gamma} - t_{offset} + t_{prop\_\_Node_j\_Node_i} = t_{data\_\delta} \end{cases} \tag{2}$$

The transmission delay of packets sent by $Node_{\mathrm{i}}$ and $Node_{\mathrm{j}}$ can be considered to be the same as that of $t_{prop\_Node_i\_Node_j}$ and $t_{prop\_\_Node_j\_Node_i}$ when the network topology does not change significantly and the operational usage environment does not change significantly in an instant. Then:

$$\begin{cases} t_{offset} = [(t_{data\_\beta} - t_{data\_\delta}) - (t_{data\_\alpha} - t_{data\_\gamma})]/2 \\ t_{prop\_Node_i\_Node_j} = [(t_{data\_\beta} + t_{data\_\delta}) - (t_{data\_\alpha} + t_{data\_\gamma})]/2 \end{cases} \tag{3}$$

4 Optimal Dijkstra Routing Mechanism Based on Mac Layer Blocking Degree

In the case that the node transmission range and the transmission rate of wireless transmission module are fixed, the transmission delay of one-hop distance is basically a fixed value. However, the packets in the cluster network usually arrive at the destination node through multi-hop transmission, and the effective way to reduce the total delay is to reduce the total number of hops that the packets pass through.

The path selection scheme studied uses Dijkstra's algorithm to select the path with the minimum number of hops. Given that the computational power of a single node is more limited, this scheme uses a binary heap to optimise the Dijkstra algorithm. Optimising the action of finding the minimum distance node in the traditional Dijkstra algorithm to use a priority queue can reduce the time complexity from $O(V^2)$ to:

$$O((E + V)ln\,V) \tag{4}$$

where V represents the number of nodes in the swarm network and E represents the number of effective links, which is consistent with the shortest path finding in the environment of weak computational power of the swarm.

In the topology graph, each node uses its MAC layer cache usage c as a point right to effectively reduce the queuing delay of the node through different path choices. c is calculated by the following equation:

$$c = \frac{num_s + num_t + num_{\mathrm{re}}}{L} \tag{5}$$

where num_s packets to be sent, num_t packets to be forwarded, num_{re} packets to be retransmitted, L buffer size.

To calculate the shortest path, first follow the traditional Dijkstra's algorithm to find the link with the shortest overhead, when the lengths are the same compare the point weights, i.e., the MAC layer blocking degree, select the node with small cache usage to join the path and update the total MAC layer blocking degree of the path, the logic of the algorithm is demonstrated in Algorithm 1:

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Input: topology graph $G$, starting node $s$, node MAC layer blocking degree $c$
Output: the shortest path of $s$ to the remaining nodes in the graph, taking into account any blocking.
for vertex $v \in G.V$
    $v.d=\infty$
        $v.pre=None$
end for
$s.d=0$
$S=\emptyset$, $Q=G.V$
while $Q\neq 0$
    $U$=The set of minimum distance nodes in $Q$
      if $U.length=1$
        $u=U[0]$
      else
        $u$=The node in $U[0]$ with the smallest $cost$
    $S=S\cup\{u\}$, $Q=Q-\{u\}$
      for unvisited vertices $v \in G.Adj[u]$
        if $v.d > u.d + w(u,v) || (v.d = u.d + w(u,v) \&\& v.c > u.c + cost(u,v))$
          $v.d = u.d + w(u,v)$
          $v.c = u.c + cost(u,v)$
          $v.pre = u$
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Algo.1 Dijkstra Algorithm Based on Node Blocking

This routing scheme, proposed by Dijkstra, takes into account the degree of blocking at the MAC layer. It optimizes the selected paths to reduce the average queuing delay between nodes while minimizing the transmission delay. Additionally, it effectively reduces the information transmission delay within the swarm at two levels.

5 Relay Node Delay Guarantee Mechanism Based on New Dynamic Flow Token Bucket

Due to the aerial high dynamic node combat modes, complex combat scenarios, the existence of nodes with random access, and the possibility of destruction by enemy ground or air interceptor weapons, the distribution of nodes in the bomb group network is relatively dense and variable. As a result, there are many paths to choose from between the bomb groups. The Dijkstra routing mechanism based on the blocking degree of the MAC layer can effectively reduce the queuing delay of packets sent by nodes before arriving at relay nodes. However, it cannot solve the problem of a large number of packets queuing at the relay nodes. This section proposes a mechanism for guaranteeing relay node delay using a new dynamic flow token bucket limiting algorithm [17]. The mechanism limits the speed of ordinary nodes adjacent to the relay node, ensuring an upper bound on the queuing delay at the relay node. This reduces queuing delay and packet loss due to queuing at the relay node.

Assuming that the packet size is *P* bits and the transmission rate of the relay node is r bps, when there are m packets arriving at the relay node one after another, the queuing waiting delay of the last packet to be processed is the total service processing time of the first m - 1 packets, i.e.:

$$t_{\text{queue}} \leq (m-1) \times \frac{P}{r} + t_{\text{process}} \tag{6}$$

When each ordinary node in the grouped operational swarm sends multiple packets, assuming that the queue of the relay nodes is idle at the initial moment, if it can be guaranteed that each ordinary node sends only one packet during the service delay period, i.e., during the time t_{quene}, it can be guaranteed that there is a deterministic upper bound for the queuing delay of the individual relay nodes during each service delay period. In contrast, the sending rate of ordinary nodes needs to be limited to

$$R = \frac{P}{t_{\text{queue}}} \approx \frac{r}{m} \tag{7}$$

A new flow limiter type, the Dynamic Leaky Token Bucket Limiter [17] (DLTB), has been developed to achieve speed limiting for ordinary nodes within the swarm and to ensure the boundedness of the queuing delay of relay nodes. The DLTB design incorporates the Leaky Bucket algorithm concept into the traditional Token Bucket (TB) design. In a Token Bucket flow limiter, data transfers consume tokens generated in the bucket at a fixed rate. By controlling the rate of token generation, the network can receive data at a controlled rate, allowing for the transmission of bursty data. In contrast, the Leaky Bucket flow limiter places packets in a bucket and releases them into the network at a constant rate, smoothing out bursty traffic in the event of a change in swarm status due to interception targets or changes in topology resulting from operational changes.

Ordinary nodes use DLTB to limit the flow as shown in Fig. 2. The dynamic flow token bucket converts the packets in the leaky bucket into tokens, every e_{sw} seconds a fixed P_{max} token will be added to the bucket of size P_{max} at one time and the tokens in the bucket will be leaked out of the bucket at the rate of r = $P_{\max}$ /e_{sw}. Therefore when

P_{max} tokens are added, each packet transmission consumes the tokens in the bucket and cannot be sent if there are no tokens in the bucket. The dynamic flow token bucket will be exhausted after a maximum of e_{sw} seconds and will be refilled when the next token is added. It can be observed that the average rate of token joining is the same as the rate of token leakage, and the tokens in the dynamic flow token bucket will be emptied at the end of each e_{sw} cycle if no packets arrive, and the bucket will be emptied faster if packets arrive and up to the size of P_{max} is sent each cycle. Therefore, the dynamic flow token bucket ensures that the ordinary nodes satisfy the flow limiting requirements of Eq. (7), thus guaranteeing a bounded queuing delay at the relay nodes.

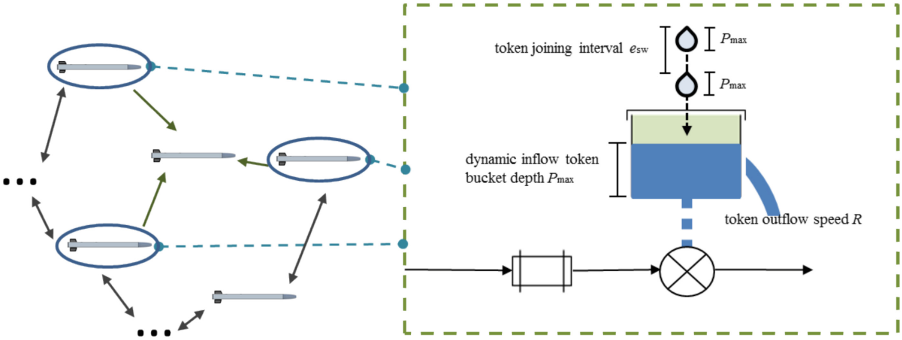

Fig. 2. Network nodes connected to relay nodes using DLTB

This scheme aims to reduce the high latency and packet loss of relay nodes caused by queuing. Simulation analysis of the queue length of the relay node, with and without speed limits for the neighboring node, is shown in Figs. 3 and 4.

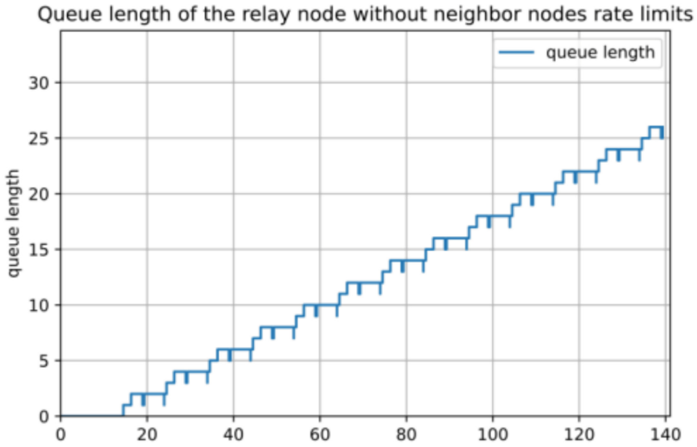

Fig. 3. Queue length of the relay node without rate limit for neighbor nodes

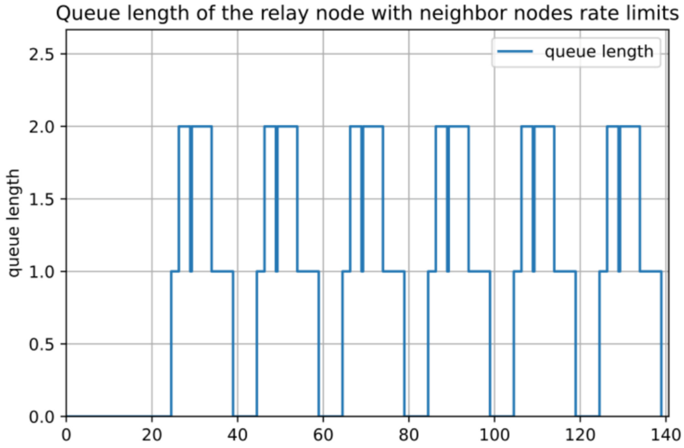

Fig. 4. Queue length of the relay node with rate limit for neighbor nodes

The queue length of the relay node gradually increases over time when there is no speed limit, indicating a corresponding increase in the queuing delay of arriving packets. However, when a neighborhood speed limit is in place, the queue length of the relay node varies periodically and has an upper bound. This represents an upper bound on the queuing delay of arriving packets, which ensures that the queuing delay at the relay node is limited.

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