Abstract—In this paper, we consider traffic network with high-speed mobility nodes scenario; and give a new network topology control mechanism to rise the routing path duration in Aeronautical ad hoc network. The mechanism can use different methods to construct topology according to the node densities. For network regions having a high density of aircraft; the packets are preferentially routed over the long available links created by the aircraft moving in same direction. For low density of aircraft; the routing preferentially uses the short available links created by the aircraft moving in both directions. The mechanism can effectively decrease the probability of routing path breaks; when the nodes move with a high velocity. It can be also integrated with existing Ad hoc network routing protocols smoothly. We combine the mechanism with Optimized Link-State Routing Protocol (OLSR); and give a Path Link Availability Routing Protocol (PLAR). The performance of PLAR protocol is compared with several routing protocols in different scenes. The metrics include end-to-end delay; availability and length of path. Experimental results show that PLAR protocol exhibits a significant improvement over most routing protocols base on topology and position.

Index Terms—Topology Control; Routing Protocol; Ad Hoc; Mobile Computing; Wireless Network

I. INTRODUCTION

AANET (Aeronautical Ad Hoc Network) is a kind of Ad Hoc Network. AANET has its own features compared with the traditional MANET. In the AANET; the mobile speed of nodes is generally higher. The mobility of aircraft is usually constrained by flight path. And the nodes are not constrained excessively in terms of energy. The rapid change of network topology in course of moving leads to frequent link break between nodes. And it will cause frequent routing path interruption; which can bring great influence for the persistent session established by applications. These problems have brought new challenges to routing protocol in AANET; which require the routing protocol can detect the frequent network topology change and cope with it with effective methods. Comparing AANET with MANET; the mobility of nodes in AANET has certain regularity and controllability. And the available time of link is considered a crucial metric for high mobility of AANET. The routing protocols adopt the links with long available time in the process of routing path build; which can increase the stability and reliability of the routing path greatly.

The current routing protocols used in MANET can be divided into two categories [1-2]: topology-based and position-based.

In topology-based routing mechanisms; the nodes need store routing tables or routes which depend on the topology. This kind of protocols includes the AODV (Ad hoc On-Demand Distance Vector Routing); OLSR (Optimized Link State Routing) and others (DSDV; DSR; TORA and FSR). Strictly speaking; these protocols were proposed for MANET; where the nodes are assumed to move with low velocity and frequency. On this condition; these protocols are allowed to establish available end-to-end paths within a reasonable time range. And they only occasionally need repair the path according to the movement features. Consequently; this kind of protocol is used for AANET; which is not easy to meet various requirements of applications. Especially when various aircrafts move with high-speed; these protocols are difficult to meet the demand of real-time data transmission. Therefore; the protocols based on topology in MANET are used for AANET; which faces some challenges. One of the key problems is nodes in AANET usually require updating the routing information in quasi real time; in order to perceive the change of network topology in time. And it can cause high cyber resources consumption. And some optimization can alleviate the consumption; such as the design of a lightweight protocol based on link state aware in [3]. For high mobility scenarios; the nodes exhibit some special characteristics in [4]; which shows some routing protocols proposed for MANET can not perform well in AANET.

The position-based routing protocols mainly include GSR; GPSR; LORA_CBF; RBVT; GyTAR and COALS; etc [5-10]. This class of protocol often uses the location of the neighbor nodes and destination node to determine the next hop node. In most cases; the nodes do not need
record any address or routing table for forwarding packets; only record the corresponding position of nodes. But these protocols also have their negative side. For example; when a fault occurs in positioning system of node; in order to inform other nodes of its new location; the node must broadcast its location to other nodes; which will increase the consumption of cyber resource.

The comparison study about routing protocols for AANET is few currently. Literature [5] has compared the data transmission performance of AODV and OLSR protocol in mobile Ad hoc network with mobile trajectory constraint; including the routing path length; packet delivery ratio; routing overhead and end-to-end delay. It makes a conclusion that the performance of OLSR protocol is better than AODV protocol in above scenario. The performance of AODV; DSR; TORA and FSR routing protocols have been compared in high speed mobile Ad hoc networks [6]. And the study results show the performance of AODV and FSR are better; the DSR and TORA are unsuitable for high speed mobile ad hoc networks. Since the forwarding efficiency of TORA shows poor performance and the end to end delay of DSR is too high. A comparison of city traffic models based on high speed mobile ad hoc network is carried out in [7]. The different routing algorithms in MANET are compared in several traditional performance metrics [11-12]; such as path length; end to end delay; packet forwarding rate; routing overhead and so on. However; the available time; an important metric for routing in AANET; is still lacking for network stability metrics. Literature [13] takes TCP protocol as an example; and point out that the routing failure occasioned by path break lead to TCP connection interruption. And the handshake mechanism of TCP may cause entire network serious instability; which demonstrates that the path available time plays an important role in network stability.

This paper focus on routing mechanism based on topology in AANET. We aim to provide an ideal environment for the applications in AANET; which is not relying on positioning system. The rest of the paper is organized as follows. Section 2 introduces the nodes mobility models in AANET. In Section 3 we describe a topology control mechanism based on nodes mobility models in AANET. Section 4 describes a routing mechanism based on high mobility of node in AANET. Section 5 addresses the simulations and the evaluation metrics that we adopted. Section 6 presents the analysis of simulation results. Finally; the summary and outlook are given in Section 7.

II. NODES MOBILITY MODEL IN AANET

Mobile nodes in AANET are usually all kinds of air vehicles. Each air vehicle always moves along different flight routes in accordance with all assigned missions. And the flight path is always a straight line. The same flight route usually has two different directions; one is the direction which air vehicles start off on their missions; another is direction homed at end of missions.

Our research focuses on the theoretical method of network construction; when air vehicles flight along bidirectional straight line route. The following is an instance of the theoretical model.

We adopt the following assumptions: set the distance between two air vehicles $m_1$ and $m_2$ to $d$; the radio communication range of each node is $r$; the velocity of two air vehicle nodes $m_1$ and $m_2$ are represented by the vectors $v_1$ and $v_2$ respectively. A link between two nodes is created if $d < r$. We consider two cases: when the nodes move with high speed; the link between the nodes will remain active in the case of $v_1 = v_2$; the link will be broken after some time if $v_1 \neq v_2$. According to the flight characteristics of the air vehicles on the same route; $v_1$ and $v_2$ can be represented in polar coordinates $(v_1, \theta_1)$ and $(v_2, \theta_2)$ with $v_1, v_2 \in [V_{min}, V_{max}]$ and $\theta_1, \theta_2 \in [0; \pi]$, the relative velocity of the nodes is represented by

$$v_r = v_1 - v_2 = (v_1 \cos(\theta_1) - v_2 \cos(\theta_2), v_1 \sin(\theta_1) - v_2 \sin(\theta_2))$$

And we define its absolute value as

$$|v_r| = \sqrt{v_1^2 + v_2^2 - 2v_1v_2\cos(\theta_1 - \theta_2)}$$

As the random variables in (3) are independent; the joint distribution function $f(v_r)$ is equal to the product of the marginal distribution function $f(v_r) = f(v_1)f(v_2)f(\theta_1)f(\theta_2)$.

The mathematical expectation of relative velocity can be expressed as

$$E(v_r) = \int_{V_{min}}^{V_{max}} \int_{V_{min}}^{V_{max}} \int_{0}^{\pi} \int_{0}^{\pi} f(v_1)f(v_2)f(\theta_1)f(\theta_2)$$

$$\frac{v_1^2 + v_2^2 - 2v_1v_2\cos(\theta_1 - \theta_2)}{d \theta_1 d \theta_2 d v_1 d v_2}$$

Figure 1. Maximum relative displacement between two mobile nodes without broken their link

We assume that two nodes $m_1$ and $m_2$ form link$_{12}$ at instant $t$; and consider that node $m_1$ moves with velocity $v_r$ relative to node $m_2$; the link$_{12}$ will be considered broken after some time if $|v_r| > 0$. If nodes do not change their velocity and the relative distance traveled never
exceeds $2r$ during the interval $(t, t+\Delta t)$; the nodes will maintain the link $k_{12}$ active. This scenario is depicted in Fig. 1.

The probability of a link formed at a time $t$ remaining active at a time $t+\Delta t$ is related with the spatial intersection of the covered areas at instants $t$ and $t+\Delta t$, which is represented by the white area in Fig. 2.

The radio covering area of the node $m_1$ at instant $t$ can be depicted by following formula

$$C_t = 2\int_0^r \sqrt{r^2 - x^2} \, dx$$  \hfill (5)

The radio covering overlap area in the instant $t$ and $t+\Delta t$ can be represented by function $O_{t+\Delta t}(d)$ which is the node $m_1$ move with velocity $v_1$ in the interval $(t; t+\Delta t)$ (the distance $d>0$)

$$O_{t+\Delta t}(d) = \frac{\pi r^2 - \frac{\pi}{2} \sqrt{r^2 - x^2} \, dx}{d>2r}$$  \hfill (6)

\begin{center}
\caption{Radio covering circumference change of the node $m_1$ moved $d$ length units between instant $t$ and the time instants $t+\Delta t$}
\end{center}

Now we take the hello message in routing mechanism based on topology (DSDV; AODV or OLSR protocol) as an example; and introduce the method for calculating link available probability in the process of nodes moving. We consider that the Hello messages are broadcasted every $T$ seconds to discover and/or maintain an active link. The distance; which the node $m_1$ move relative to the node $m_2$ during the period $T$; can be calculated by $E(V_i)T$. Therefore; the probability of the link remaining active after $nT$ periods is approximately depicted by Formula (7). (N denotes the set of natural numbers)

$$P_{\text{connected}}(n) = \frac{O_{nT}(nTE(V_i))}{\pi r^2} \quad n \in N$$  \hfill (7)

We consider the nodes moving with high speed only have two opposite directions. When the nodes move in the same direction; the mathematical expectation of relative velocity can be calculated by the formula (8); which is simplified by formula (4).

$$E_{\text{same direction}}(V_i) = \int_{v_{\min}}^{v_{\max}} \int_{v_{\min}}^{v_{\max}} f(v_1)f(v_2)$$  \hfill (8)

When the nodes move in the opposite direction; the mathematical expectation of relative velocity can be calculated by the formula (9) which is simplified by formula (4).

$$E_{\text{opposite direction}}(V_i) = \int_{v_{\min}}^{v_{\max}} \int_{v_{\min}}^{v_{\max}} f(v_1)f(v_2)$$  \hfill (9)

\begin{center}
\caption{Proposition 1}
\end{center}

The links established by the nodes flight in the same direction take on a higher probability of keeping long time available than in opposite direction on one air line.

\textbf{Proof}. The known periodic $T$ is a constant. And the relative distance $d = E(V_i)nT$ between two moving nodes is proportional to the expected relative velocity $E(V_i)$. We can get $E(V_i)\text{opposite direction} > E(V_i)\text{same direction}$ by formulas (8) and (9). And $O_{t+\Delta t}(d)$ is a decreasing function in $0 \leq d \leq 2r$.

By the known conditions and formula (7) can infer

$$\frac{O_{t+\Delta t}(nTE\text{opposite direction}(V_i))}{\pi r^2} > \frac{O_{t+\Delta t}(nTE\text{same direction}(V_i))}{\pi r^2}$$

Therefore; when the nodes move in the same direction; the probability which the links between two nodes keep long time available is higher.

When the routing protocols in AANET create multi hop routing path; using proposition 1 can effectively reduce the probability of link break; thereby reducing the probability of routing path interrupt. When the density of air vehicles is smaller; the links created by the air vehicles in the same direction may not ensure the interactive data between the two nodes can be delivered each other. So we need use the links created by the nodes flight in the opposite direction. Under the circumstances; the proposition 2 can be introduced to optimize the routing mechanism and increase the available time of routing path.

\begin{center}
\caption{Proposition 2}
\end{center}

The newest links established by the nodes flight in the opposite direction take on a higher probability of keeping long time available than older links on one air line.

\textbf{Proof}. Set a time period $T$ and two links $link_1$ and $link_2$ created at different time. At the time instant $t$; the $link_1$ has lasted for $nT$ ($n \in N$); and the $link_2$ has lasted for $(n\beta)T$ ($0 < \beta < n$; $\beta \in N$). According to the formula (7); the probabilities that the $link_1$ and $link_2$ keep available at the time instant $t$ are respectively represented by

$$P_{\text{connected}}(n) = \frac{O_{nT}(nTE\text{opposite direction}(V_i))}{\pi r^2}$$

and

$$P_{\text{connected}}(n-\beta) = \frac{O_{n\beta}(n-\beta)TE\text{opposite direction}(V_i))}{\pi r^2}$$

Since $O_{t+\Delta t}(d)$ is a decreasing function in $0 \leq d \leq 2r$; Thus; we can get $P_{\text{connected}}(n) > P_{\text{connected}}(n-\beta)$. And the probability which the older $link_1$ keeps available is smaller.

\section{III. Topology Control Base on Mobility Model}

This section introduces a solution which uses topology control mechanism to detect and recognize the available link established by two nodes flight on one air line in AANET. In routing mechanisms based on topology
control; we mainly adopt regular exchange of Hello packets to discovery and maintenance the link between two nodes. Therefore; we represent the available time of a link by the number of Hello packets received; and introduce the concept of node logic neighbor set which is the set of 1-hop nodes that can exchange Hello packets directly from one node.

Table I shows a parameter list of a logic neighbor set of $m_i$ (here $i=1$); $M$ characterizes logic neighbor set of $m_i$. $t_i(m_i)$ is the time instant when the node $m_i$ firstly receives a Hello packet from its neighbor node $m_j$; and creates a unidirectional link between them. $\phi_i(m_i)$ is the stability between $m_i$ and $m_j$ used to measure the duration of link. Formula (10) is the calculation method; $t$ is current time instant; $T$ characterizes the period received Hello message; $\lfloor x \rfloor$ is the largest integer not greater than $x$.

$$\phi_i(m_i) = \left\lfloor \frac{t - t_i(m_i)}{T} \right\rfloor + 1 \quad (10)$$

| $M_i$ = $\{m_i; m_j; m_k\}$ | $\phi_i(m_i)$; $\phi_i$|$m_i$; $M_i$ | $t_i(m_i)$ | $N_i(m_i)$ |
|-----------------------------|---------------------|--------|--------|
| $m_2$                     | 69                   | 63.8   | $n_2$  |
| $m_3$                     | 12                   | 121.1  | $n_3$  |
| $m_4$                     | 4                    | 129.3  | $n_4$  |

$N_i(m_i)$ is overtime threshold. If no exchange time of Hello packets between two nodes is over the threshold $N_i(m_i)$; we consider the link is broken. And the function of $N_i(m_i)$ is to avoid that links are wrongly considered broken when occasional interference leads to Hello packet loss. Here; we just consider a fixed value: $N_i(m_i) = 4T$; which means that the link detection mechanism tolerates up to three consecutive missed Hello packets and does not deem it broken. The probability of more than three consecutive missed Hello packets is small [14-15]. And when there is not Hello packet exchanged via a link for 4 periods; the link is considered broken; the routing algorithm no longer chooses this link; its stability value is reset. However; when the stability value reaches a threshold again; the link will be reconsidered as an available link again.

A. Recognition of Long Time Available Links

This subsection gives a method using the stability value to detect the long time available link between the air vehicles flight in the same direction. As shown in the formula (11); a link is considered to have high stability if its stability value $\phi_i(m_i)$ is greater than a given value $n_{stab}$. And we define the link with high stability as a long time available link (represent with $link_{\text{stabil}}$).

$$\phi_i(m_i) \geq n_{stab} \quad (11)$$

Following is the calculation method of $n_{stab}$. Based on the formula (6) and (7); a link created by two nodes flight in the opposite direction presents an improbability of keeping the link available when $d > 2r$ and $E(V) \neq 0$. Due to $d = E(V) \cdot n \cdot T$; we can infer $p_{\text{connect}}(n) = 0$ when $n > 2rE(V)/T$. The literature [14] finds that keeping the link available in high speed Ad hoc network; relative velocity is approximated by a normal distribution; $99.7\%$ of the velocity observations are within $E(V) \pm 3 \sigma < E(V)/3$; where $\sigma$ denotes the standard deviation of the distribution. And we use the lower limit $E(V) - 3 \sigma$ of relative velocity distribution to get a larger $n_{stab}$ value. The computational method is shown in formula (12).

$$n_{stab} = \frac{2r}{(E(V) - 3\sigma)/T} \quad (12)$$

In other words; after the link is created between two nodes flight in same direction; more than $n_{stab}$ Hello packets are transmitted; which means the link is a long time available link.

B. Recognition of Short Time Available Links

The links between nodes are not always long time available links for the mobility of the nodes in AANET. Sometimes all existing long time available links can not establish a routing path. On this condition; we need some short time available links to patch the routing path for reliable data transmission. When the condition $\phi_i(m_i) < n_{stab}$ holds; a link is considered to be unstable. The unstable link with longer duration is defined as short time available link. And corresponding recognition algorithm uses the proposition 2 to select the nodes which create link with minimum stability value from logic neighbor set; as shown in the formula (13).

$$link_{\text{stab}} = \min(\phi_i(m_i)), \quad \forall m_i \in M_i \quad (13)$$

For the unstable links; we do not distinguish the links created by the nodes flight in the same direction or the opposite direction; and just choose the link with minimum value of $\phi_i(m_i)$ as the short time available link.

C. Topology Control Based on Link Stability

When majority of logical neighbor nodes have created long time available links between themselves and a node; we consider the node as a stable node. It can be used for broadcasting the messages about network topology change. To avoid a large amount of messages broadcast causing flooding phenomenon; we propose a broadcast agent vote algorithm; which can select an agent node to broadcast the messages about network topology change. In addition; the topology consists of long time available links can be effectively used for information dissemination and transfer in whole network.

We assume $A_i(m_i)$ is the broadcast agent selected by node $m_i$; and only one broadcast agent can be selected by node $m_i$. The $m_i$ also can learn of other broadcast agents selected by the nodes in its logical neighbor set via the Hello message. The detail is shown in algorithm 1.

Algorithm 1. The node $m_i$ selects its broadcast agent.

Input: $M_i$; $\{\phi_i(m_i); A_i(m_i); (m_i) \} \forall m_i \in M_i$.

Output: $A_i(m_i)$

1. $\phi_{\text{stab}} \leftarrow \text{return}_{\phi_{\text{stab}}}$ from_table();
2. $\text{address} \leftarrow \text{MAX}_{\text{INT}}$;
3. $A_i \leftarrow -1$;
4. $\text{threshold} \leftarrow -1$;
5. IF $\text{if \_stable \_node} (m_i) \text{ THEN}$
6. $\text{FOR each neighbor} m_j \in M_i \text{ DO}$
7. $\text{insert\_list}(A_i(m_i), \text{list\_BA})$;
The principle of the algorithm as follows:
First; when there is not long time available link between \( m \) and its logic neighbor nodes (meaning that \( m \) does not have stable neighbors); \( m \) does not select any node as its broadcast agent;
Second; when the logic neighbor nodes of \( m \) do not select \( m \) as their broadcast agent; and there is at least one neighbor node \( m \) is already a broadcast agent; \( m \) select \( m \) as its broadcast agent. We can merge multiple broadcast groups into one through this rule.
Third; when \( m \) is one of broadcast agents selected by the logic neighbor nodes of \( m \); and the address of \( m \) is lower than broadcast agents of its neighbor nodes; \( m \) selects itself as a broadcast agent. The function of this rule is to merge multiple broadcast groups into one when \( m \) act as the broadcast agent of the group.
Last; when none of logic neighbor nodes of \( m \) has a broadcast agent; \( m \) selects the node; which has maximal stability value and lowest address in logic neighbor nodes of \( m \); as its broadcast agent. This rule is used to select the first broadcast agent in the network.

IV. ROUTING MECHENISM BASE ON MOBILE FEATURE OF NODES IN A NNET

This section introduces a new protocol Path Link Availability Routing Protocol (PLAR) based on OLSR. And one feature of PLAR is using the stability of link to control the network topology. A core technology used in OLSR is Multipoint relaying (MPR); which can reduce the number of redundant retransmission message when the messages are broadcasted in the network. The Multipoint Relay Set (MPRs) is a set of Multipoint Relay nodes. In OLSR; MPRs are chosen as the minimum set of \( m \)'s 1-hop neighbor nodes which cover all its 2-hops neighbor nodes. Therefore MPR nodes can guarantee 2-hops full coverage. Algorithm 1 can generate a broadcast agent set which send the message about topology change; and construct a stable topology which diffuse the message in whole network. Then we introduce the algorithms 2 and 3; which select and generate the MPRs based on the algorithm 1. The algorithm 2 relates to the method of generating MPRs; when the density of mobile nodes is high. And Algorithm 3 is used to generate MPRs and supplementary MPRs for low density of nodes.

A. Generation of MPRs for High Density of Nodes

This subsection introduces a new method (algorithm 2) generating MPRs for the OLSR protocol based on algorithm 1. The basic principle of the method is the choice of nodes with long time available links to generate MPRs. Following is an example about algorithm 2. If a given node \( m \) runs the algorithm 2; only need to know its logic neighbor set \( M_i \); stability value \( \phi_i(m) \) and 2-hop neighbor set \( M_i^2 \). In the OLSR; 2-hop neighbor set includes all 2-hop neighbor nodes of \( m \). In our algorithm; we select the 2-hop neighbor nodes; which the \( m \)'s 1-hop stable neighbor nodes \( m \) can connect with; to form the 2-hop neighbor set. The set can meet the requirement of broadcast well for topology update when the density of nodes is high. And the reason is the nodes with long time available links are enough. The core principle of the algorithm 2 is MPRs in OLSR consists of broadcast agents.

In algorithm 2; The MPRs selected in line 4 can not guarantee 100% coverage of 2-hops neighbor nodes. For example; a given 1-hop neighbor node \( m_i \) may be stable; but not be a broadcast agent. It is not selected as a MPR node in line 4. And it can be the only one that can arrive at a given 2-hops neighbor node (initially inserted in \( M_i^2 \)). All nodes contained in \( M_i^2 \) are verified in line 10; where \( M_i^2 \) should be empty if all nodes initially inserted in \( M_i^2 \) are accessible for the nodes already inserted in the MPR list. When \( M_i^2 \) is not empty; the algorithm selects the node; which has the highest stability values and can access at least one of the nodes contained in \( M_i^2 \) (selected in line 12); as the MPR node. So all 1-hop nodes have stable link to \( m_i \) can access the nodes initially contained in \( M_i^2 \). And the process of verifying and revising the MPRs is described in lines 10–15 of algorithm 2.

Algorithm 2. Generation of MPRs for high density of nodes
Input: \( M_i; M_{i}; \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
Output: \( M_i^2 \)
1 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
2 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
3 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
4 IF \( \phi_i(m) \cap n_{out} AND m_i \) is BA THEN
5 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
6 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
7 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
8 END
9 END
10 \( \phi_i(m) \cap n_{out} \) OR \( M_i \notin \phi_i(m) \cap n_{out} \)
11 WHILE \( M_i \notin \phi_i(m) \cap n_{out} \)
12 \( m_{out} ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
13 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
14 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
15 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
16 \( M_i^2 ← \phi_i(m); A_i(m); t_i(m) \cap M_i \notin M_i \)
Algorithm 2 shows better results than the MPRs generation algorithm of original OLSR when the number of stable links associated with \( m_i \) is above a given threshold (4 stable links). If the number of stable links is not above this threshold; the number of nodes contained in MPRs (Algorithm 2 in line 5) is small. But the number may become bigger in line 12. However; when the number of long time available links between \( m_i \) and its neighbors is small; the nodes initially inserted in \( M_2 \) is also small; which leads to the number of nodes in MPRs is small. Under this condition; the result of utilization proposition 2 is better than proposition 1 for the algorithm design. In the next subsection; we will introduce an additional algorithm; which is better suited for the case that the number of long time available links of \( m_i \) is below the threshold.

B. Generation of MPRs for Low Density of Nodes

When the density of air vehicles is low; the number of long time available links created between the air vehicle and its neighbors is small. The result of algorithms 2 is not ideal. Under this condition; we can utilize more short time available links to increase the amount of routing path; thereby improving the routing efficiency. Therefore; this subsection gives the algorithm 3 based on proposition 2 to generate MPRs for the lower density of nodes.

Algorithm 3. Generation of MPRs for low density of nodes

Input: \( M; M_2; \phi(m_i); A(m_i); t(m_i) \) \( \forall m_i \in M \)

Output: MPRs(\( m_i \))

1. MPRs(\( m_i \)) \( \leftarrow \) \( \emptyset \)
2. \( M_2 \leftarrow \text{2-hop_neighbour}(\phi(m_i)) \)
3. FOR each neighbor \( m, \in M \): DO
4. IF \( \phi(m_i) \cap m \) \( \cap \emptyset \) AND \( m \) is BA THEN
5. MPRs(\( m_i \)) \( \leftarrow \) MPRs(\( m_i \)) \( \cup m \)
6. remove_2_hops_from(\( M_2 \))
7. remove_1_hops_from_set(\( m_i; M \))
8. END
9. END
10. \( M_{2a} \leftarrow \text{sort_stability_by_ascendent}(M) \)
11. WHILE \( M_2 \neq \emptyset \) : DO
12. \( m \leftarrow \text{get_first_element}(M_{2a}) \)
13. MPRs(\( m_i \)) \( \leftarrow \) MPRs(\( m_i \)) \( \cup m \)
14. remove_2_hops_from(\( M_2 \))
15. remove_1_hops_from_set(\( m; M \))
16. rm_redundance_cover(\( N_{1a} \) from_set(MPRs(\( m_i \)); M_{2a})
17. END;

Algorithm 3 has the same rationale with algorithm 2. The 1-hop neighbor nodes of \( m_i \) which have been selected as broadcast agents and have long time available links with \( m_i \) are inserted in MPRs (lines 3–8); since these links are stable. Proposition 1 indicate that they have higher probability of keeping available for a long time. If the nodes contained in MPRs generated based on proposition 1 can not access all 2-hop neighbor nodes; the algorithm inserts more unstable nodes into MPRs (lines 10 to 15). For this case; the density of nodes is low; and algorithm 3 uses proposition 2 to select the 1-hop neighbor nodes; which have lowest stability value links to \( m_i \); as the nodes of MPRs. And the link between \( m_i \) and its neighbor nodes with lowest stability value has higher probability of keeping long time available.

C. Selection Policy of Algorithm in PLAR

The difference between the algorithm 2 and algorithm 3 is the way of generating the MPRs. When the density of air vehicles is high; the probability of creating more long time available links between \( m_i \) and its neighbor nodes (stable neighbor nodes) is high. So the algorithm 2 is applied. For low density of air vehicles (scenario proposed for Algorithm 3); the probability which the 1-hop stable neighbor nodes of \( m_i \) can access all 2-hop neighbor nodes of \( m_i \) is lower. At this moment; algorithm 3 is more suitable.

A given node \( m_i \) running our method uses Algorithm 2 or Algorithm 3 depending on the number of its long time available links. We set a threshold. If the number of long time available links associate with \( m_i \) is not greater than the threshold. The node \( m_i \) adopts the Algorithm 3. Otherwise; Algorithm 2 is used to generate the MPRs. In our work; we set the threshold at four; which was achieved by simulating different threshold values for both Algorithms 2 and 3. From the results of simulations performed; we conclude that the performance of algorithm 3 is better than the Algorithm 2 when the number of long time available links is less than 5. If the number of long time available links is more than four; Algorithm 2 presents better performance than algorithm 3.

V. SIMULATIONS

A. Simulation Model

In the simulation; we develop a traffic simulator to simulate air traffic scenarios. The simulator is integrated into the NS2 (network simulation platform) to simulate the AANET. We have simulated a 10 kilometer air line with three lanes in each direction. At the same time; the bidirectional air traffic with different air vehicles density is simulated. The radio range of air vehicle is 10 kilometer. We define three different classes of air vehicles according to the flying speed for a classic scenario.

We define four different scenes regarding the density of air vehicles; described in table II; which differs in the average number of 1-hop neighbor nodes. Average numbers of neighbors in simulation are adopted with 4; 6; 8 and 10 respectively; which means 5; 7; 9; 11 air vehicles per \( 10^2 \pi \) km\(^2\). The density and the simulation time of flight nodes are shown in table II. The density and simulation time setting in table II are based on real air traffic; which can reflect the normal flight states of different aircraft.

In the simulation process; we use NS2 to run the commands of air traffic simulator for aircraft communication simulation. The scheme of generating network traffic is as follows: the air vehicles flight from west to east generate the packets; which are randomly sent to another mobile nodes. The air vehicles flight from east to west do not generate packets but are able to forward them. The number of packets generated on each density scene was maintained constant at approximately 3500 packets.
B. The Setting of Threshold \( n_{\text{sub}} \)

In order to compute the threshold \( n_{\text{sub}} \), we assume that the flying velocities of the three classes of air vehicles are normally distributed approximately. For this case; applying (8) and (9); the average relative velocity between two air vehicles flight in the opposite directions \( (E(V_{\text{opposite direction}})) \) is 589 m/s; and the average relative velocity between two air vehicles flight in the same direction \( (E(V_{\text{same direction}})) \) is approximately 15 m/s. The transmission frequency of Hello packets \( (1/T_B) \) which we adopt is 1 Hz; the maximum communication distance between nodes is 10 kilometers; the standard deviation of mobile velocities is 5 m/s. According to (12); we can yield \( n_{\text{sub}} = 68 \); which indicates the links created by the air vehicles flight in the opposite direction have low probability of lasting longer than 68 s (the probability is lower than 0.3%); and the probability in the same direction lasting for 68 s is 95.1% \( (p_{\text{connected}}(68)= O_{\text{c-d}}(68*15*1)/(\pi*10000^2)=95.1\%) \).

C. Metrics and Measure Methods

This subsection introduces the metrics and evaluation mechanisms in the simulations. We developed a packet tracking tool based on NS2. The tool is able to generate and follow every PING/PROBE packet on its way from source to destination; and record the node sequence of a routing path passed. We can easily measure the path availability; path length and end-to-end delay by simulating a specific traffic. The measurement steps are as follows:

Step 1: we choose randomly two aircrafts on the same route to compose a source-destination node pair; and one act as source; another is destination. The source node sends a PING packet to the destination node. If the PING packet can arrive at the destination node; the path is considered available; and the path availability is updated further. We use the path resolving rate to compute the path availability. The time intervals of source-destination pairs generated have exponential distribution.

Step 2: when we have confirmed the path available by using the PING packet; the time instant \( t_{\text{begin}} \) when the PING packet arrives at the destination node is recorded. And the destination node stores the sequence of nodes visited by the PING. We consider the sequence as the original path \( Path_1 \) and use it to compute the path length. At the same time; the source node sends a PROBE packet to the destination node along the \( Path_1 \) every 1 s.

Step 3: the calculation of the path available time can utilize the time instant \( t_{\text{last}} \) which the PROBE packet arrives at the destination node. When the PROBE packet is transmitted between a node pair; the destination node can verify whether the packet is transmitted along the original path \( Path_1 \). If the PROBE packet arrives at the destination node through the original path; the time instant which the last PROBE packets arrive at the destination node is recorded; and \( t_{\text{last}} \) is updated. The path available time is computed by the time instant difference \( t_{\text{last}}-t_{\text{begin}} \). If the path followed by the PROBE packet is different from the original one; then the path is considered broken. And the \( t_{\text{last}} \) is no longer updated. The final path available time is the time interval \( t_{\text{last}}-t_{\text{begin}} \); the destination node recorded lastly. And the periodic transmission of PROBE packets is canceled.

Step 4: the end-to-end delay between the node pair is computed at the destination node by the time difference \( (t_{\text{end}}-t_{\text{begin}}) \) between arrival time instant and departure time instant of one packet. We adopt the average of the time difference of packet transmission; including the PING and all PROBE packets.

VI. ANALYSIS OF SIMULATION RESULTS

We compared the simulation scenarios to the real scene; the approximation degree of all parameters and data is close to 95%. In the simulation; the performance of PLAR is compared with OLSR; DSR; AODV and GPSR.

First; the results that we analyze the end-to-end delay in simulation are shown in table III. For each protocol; the results of end-to-end delay have a common feature; that is; the end-to-end delay will increase with the increase in node density. This is mainly because the number of nodes increase will bring the number of control messages of protocol increase; which makes the ratio of network management data flow to network bandwidth increase; and increases the end-to-end delay of general data packets. However; the DSR protocol shown in Table III is an exception. Initially with the increase in density of nodes; the end-to-end delay is not increased but decreased. When the node density increases to a certain degree; the delay will increase. This is mainly because DSR uses available sub-paths contained in the cache of each node to form routing paths. When the density of nodes small; the increase of probability reusing the same sub-paths for different destination which causes the paths saturation easily. Thus end-to-end delay is increased. In addition; if the number of sub paths is small; once a sub path is break; it is hard to find other sub path to transmit the data. For this case; the packets will be discarded; resulting in higher end to end delay.

In addition; from the simulation results in table III; we also found that; with the increase in density of nodes; the end-to-end delay of DSR and GPSR is much higher than other protocols. This is because GPSR floods the position of the nodes in whole network; and DSR uses flooding to discover the path. Flooding technology is the main reason leading to the end to end delay high. And it can generate large amounts of network management data flow in the process of protocol resolving path. Therefore; DSR and GPSR are not suitable for AANET when the load of network is heavy.
The overall simulation results demonstrate that the end-to-end delay of PLAR proposed in this paper is obviously much lower than DSR and GPSR protocols; between OLSR and AODV. In point of end to end delay; performance of OLSR is slightly better than PLAR. This is mainly because the number of nodes in MPRs of PLAR is more than in MPRs optimized by OLSR; which cause more topology control messages generated and broadcasted in PLAR when the network topology update. While the bandwidth of broadcast and unicast in the simulation are 2 Mbps and 11Mbps respectively; the topology control data streams will occupy the part of common data flow bandwidth; thereby increasing the end to end delay in the process of data transmission. But compared with AODV; DSR and GPSR; PLAR has shown better performance; because the MPRs generation algorithm in PLAR preferentially selects the nodes flight in the same direction; which reduces the probability of link break; thereby decreasing the average of end to end delay.

Table IV describes the average path length of different protocols in different simulation scenarios. The OLSR shows the lowest average path length in all scenes; while DSR has the highest values for almost all scenes. Comparing the tables III and IV; we can find that the increase in average path length cause the increase of end to end delay in general. However; this does not hold for all scenes in simulation. For example; the path length in the simulation of GPSR smoothly decreases from Scene3 to Scene4; but the end-to-end delay increases from 20.08 to 29.32 ms.

In addition; for the simulation scene 2; the average path length of AODV is higher than GPSR; but GPSR shows higher end to end delay. This is because each routing protocol has its own features; can not be generalized in terms of the relationship; which the end-to-end delay is always proportionate to average path length. But when the average path length for a given protocol is smaller; and the path saturation degree is higher; it will show a higher end to end delay.

In this paper; we use the percentage of resolved paths to a given destination to define the average path availability rate. In table V; DSR and GPSR is shown higher path availability rates; the reason is a common feature of the two protocols is messages routed on demand. In addition; table V also shows the path availability rate of PLAR and AODV is very close; far higher than the OLSR. For end users; path availability rate is an important metric; but available time is also important for the network stability [13]. Although the path availability rate of DSR and GPSR in the simulation is highest; but their end-to-end delay is the highest too. In addition; there is a common shortcoming in DSR and GPSR; although they can resolve large amounts of paths to a given destination; but from the available time point view; the quality of these paths is not high.

We choose the simulation results of a medium-low (scene 2) and medium-high (scene 3) density air traffic scenarios to analyze the path available time. While the results obtained from scene 1 and 4 are similar to that obtained from scene 2 and 3; respectively; so we no longer analyze the simulation results of scene 1 and 4. In the process of analysis; we utilize the path available time cumulative distribution function (CDF) to analyze the simulation results of different protocols; as shown in figure 3. Figure 3(a) and 3(b) show the simulation results of path available time in scene 2 and 3 respectively. Combined with the results in table V; we can find GPSR and DSR have higher path availability rate; but the path available time CDF indicates that approximately 45% of the paths lasting no longer than 1 s. These values are significantly reduced in PLAR. The path available time CDF indicates the percentage of paths lasting no longer than 1 s in PLAR is smaller than 9%; significantly lower than GPSR and DSR protocols. It means the paths created by the PLAR have longer available time. In addition; figure 3(a) shows the number of paths that last no longer than 6 s is approximately 28%; while the percentages of other protocols are between approximately 55% and 78%.

| TABLE III. COMPARISON OF END-TO-END DELAY(MS) |
|---|---|---|---|---|
| scene | OLSR | PLAR | AODV | DSR | GPSR |
| 1 | 2.71±0.05 | 3.33±0.05 | 3.83±0.06 | 4.94±0.05 | 4.16±0.05 |
| 2 | 2.6±0.05 | 3.24±0.06 | 4.03±0.06 | 5.19±0.05 | 3.99±0.05 |
| 3 | 2.55±0.05 | 3.61±0.06 | 4.14±0.06 | 5.53±0.05 | 4.07±0.05 |
| 4 | 2.51±0.04 | 3.69±0.06 | 4.15±0.05 | 5.61±0.05 | 3.93±0.06 |

| TABLE IV. COMPARISON OF AVERAGE PATH LENGTH (HOPS) |
|---|---|---|---|---|
| scene | OLSR | PLAR | AODV | DSR | GPSR |
| 1 | 41.93±0.39 | 71.05±0.67 | 69.71±0.71 | 96.97±0.36 | 92.08±0.71 |
| 2 | 45.87±0.96 | 66.92±1.64 | 68.92±0.81 | 96.48±0.27 | 90.11±0.75 |
| 3 | 48.01±1.12 | 72.13±1.69 | 68.24±0.91 | 97.00±0.21 | 89.81±1.02 |
| 4 | 46.72±0.63 | 69.84±1.07 | 71.17±0.85 | 96.69±0.39 | 91.09±0.65 |

| TABLE V. COMPARISON OF PATH AVAILABILITY RATE(%) |
|---|---|---|---|---|
| scene | OLSR | PLAR | AODV | DSR | GPSR |
| 1 | 41.93±0.39 | 71.05±0.67 | 69.71±0.71 | 96.97±0.36 | 92.08±0.71 |
| 2 | 45.87±0.96 | 66.92±1.64 | 68.92±0.81 | 96.48±0.27 | 90.11±0.75 |
| 3 | 48.01±1.12 | 72.13±1.69 | 68.24±0.91 | 97.00±0.21 | 89.81±1.02 |
| 4 | 46.72±0.63 | 69.84±1.07 | 71.17±0.85 | 96.69±0.39 | 91.09±0.65 |
All simulation results show that the method proposed in this paper is applied to the PLAR; which can increase the path available time significantly. When the routing paths are created by air vehicles flight in one direction; the available rate of routing paths established by OLSR can reach 72.18%. When we choose the nodes bidirectional flight to create the routing paths; the available rate of routing paths established by OLSR is only 45.27%. The table V shows the available rate of routing paths established by PLAR using the nodes bidirectional flight can reach 66.93%; which is closer to the performance of OLSR used in a single direction. In addition; the PLAR is also shown good performance in the end to end delay; only the OLSR is superior to it. But the path available rate of PLAR is better than OLSR; which can be comparable with the AODV. Therefore; the PLAR improves on the available time for routing paths; which shows PLAR is more suitable for the AANET with higher demand on the network stability.

![Figure 3. Performance comparison of path available time](image)

VII. CONCLUSION

In this paper; we propose a new routing mechanism for AANET network. This mechanism can reduce the probability of routing path broken by increasing the available time of links in the AANET; so as to improve the performance of routing protocols. The complexity of algorithms in the mechanism are all O(n).The experimental results show that the method proposed in this paper can effectively improve the performance of routing protocols based on topology and location; mainly reflected in the path available time. The end-to-end delay and path available rate is also enhanced to an ideal level. The innovation of this paper lies in that the node mobility model of AANET is applied to the routing mechanism design and implementation. In the future; we can further research on probability model representing the real-time parameters of node mobility model; which can provide a theoretical basis for the adaptive routing behavior in AANET.

ACKNOWLEDGMENT

The author wishes to thank the anonymous reviewers for their valuable comments and suggestions. This work was sponsored by the Natural Science Foundation of China (NSFC) under Grant No. 61303225; the Natural Science Foundation of Shaanxi Province of China under Grant No. 2013JQ8046; the Basic Research Foundation of Northwestern Polytechnical University under Grant No. GBKY1004.

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**Zhong Dong** received the BEng degree of information security in 2002; MEng degree of software engineering in 2005; and PhD degree of engineering in computer science and technology in 2010; respectively; from the Northwestern Polytechnical University. He is currently a lecture at the School of Computer Science; Northwestern Polytechnical University; P.R. China. His research interests include mobile computing; Aeronautical Ad Hoc Network; and Internet of things. He is a member of the IEEE; ACM and CCF.