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Effective local dynamic routing strategy for air route networks

Wu Wenjun *, Zhao Lingxi

School of Electronic and Information Engineering, Beihang University, Beijing 100191, China

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Abstract With the rapid development of air transportation, network service ability has attracted a lot of attention in academe. Aiming to improve the throughput of the air route network (ARN), we propose an effective local dynamic routing strategy in this paper. Several factors, such as the routing distance, the geographical distance and the real-time local traffic, are taken into consideration. When the ARN is in the normal free-flow state, the proposed strategy can recover the shortest path routing (SPR) strategy. When the ARN undergoes congestion, the proposed strategy changes the paths of flights based on the real-time local traffic information. The throughput of the Chinese air route network (CARN) is evaluated. Results confirm that the proposed strategy can significantly improve the throughput of CARN. Meanwhile, the increase in the average flying distance and time is tiny. Results also indicate the importance of the distance related factors in a routing strategy designed for the ARN.

1. Introduction

With the continuous growth of the global economy, the air transportation network is confronted with heavy traffic. In China, the air transportation traffic grew at an exponential rate with seasonal fluctuations.[1] The research on improving the air transportation network service ability has attracted a lot of attention in academe.

One of the most popular approaches to overcome airports' congestion has been the allocation of ground delays to departing flights.[2–5] Moreover, research literature also noticed that very significant delays and system throughput degradations had arisen from en-route airspace problems and limitations.[6] Considering the dynamic behavior of air transportation, the rerouting problem was discussed. In the modeling of the rerouting problem, a set of alternative routes and a set of possible slots of departure were predefined for each flight. The target was to select the best route and departure time. To improve the computational performance, integer optimization approach,[6] genetic algorithm[7,8] and mixed-integer linear programming were adopted.[9] However, these rerouting methods were based on sectors in the airspace, the more detailed elements of airspace, i.e., air route segments (ARSs) and air route waypoints (ARWs), were not considered.

* Corresponding author. Tel.: +86 10 82317846x6312.
E-mail address: wenjunwu@buaa.edu.cn (W. Wu).

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The air route network (ARN), which consists of ARSs and ARWs, is the backbone and the most fundamental infrastructure of air transportation system.[10] It supports all the flight activities of civil aviation. As opposed to its importance, research literature dealing with routing strategies for the ARN is quite sparse. Zhang et al. studied optimal flight routes and departure slot-times for all the involved flights, with the aims of both minimizing the total flight delays and maximizing the airlines fairness in ARN.[11] The route of each flight was chosen from a predefined optional path set, which was similar to the rerouting methods based on sectors. Xu proposed a more flexible dynamic routing strategy based on the node capacity utilization in his doctoral dissertation.[12] However, the strategy needed to calculate the path from the current location to the destination for each flight at each time slot. The computational complexity of the dynamic routing strategy was not good enough for real-time application.

As mentioned above, the dynamic routing strategy and the routing-throughput-relation in the ARN have not been fully investigated. Hence, it will be very meaningful to explore these research topics.

In the research field of complex networks, a lot of related works have been published.[13–19] The critical point of phase transition from free-flow state to congestion state has been used to indicate the network throughput in a lot of research papers. Yan et al. proposed a degree-based routing strategy to avoid the nodes with higher degrees and re-distribute the traffic.[13] Based on the routing protocol proposed by Yan, a shortest-remaining-path-first queuing strategy was introduced.[14] For large networks, a routing protocol only based on local topological information with a single tunable parameter was presented.[15] Using this local routing protocol, the relation between the time-to-live and the critical point of phase transition from free-flow to congestion was discussed.[16] Considering the limitation of link capacity, a routing strategy was proposed based on topological distance, link capacity and betweenness.[17] For spatial scale-free networks, choosing a neighbor with a higher degree in the local routing strategy can also give a higher probability of taking a short-cut in the next iteration.[20]

Although these routing strategies proposed in research literature cited above can improve the performance of scale-free networks, they are not designed for the ARN. Indeed, the ARN is not a scale-free network.[10] The relation between the degree and betweenness in the ARN is not strictly positive and there exist no obvious degree–degree correlations.[10] Thus the degree-dependent routing strategies neither redistribute the traffic uniformly nor help to find the short-cut. Besides, ARN is a transportation network whose nodes are embedded in the Euclidean space and whose edges are real physical connections. The geographical distance is relevant to the fuel-cost and much more important than the topological distance (hops). The flying distance and the traffic state are relevant to the safety of aviation. Thus the geographical distance and the traffic state must be considered in the routing strategy for ARN.

Aiming to improve the throughput of the ARN, we propose a local dynamic routing strategy for ARN in this paper. For a certain flight, the next step ARW is calculated before the flying on the current ARS is finished. Since the fuel and flying distance of a flight is limited, the distance information is considered as the primary factor in the cost function to ensure the traveling distance in the ARN is in control. To improve the utilization of en-route airspace resources, the real-time traffic information is also considered, which will avoid traffic accumulating at some nodes and help to redistribute traffic. A tunable parameter for the distance factor is proposed, and its best value is explored. We apply the proposed local dynamic routing strategy to the Chinese air route network (CARN). Results confirm the importance of the distance related factors in the ARN. Results also confirm that the throughput of CARN is improved, while the average flying distance and time is not markedly increased.

The rest of this paper is organized as follows. In Section 2, we introduce the time–space network model of the ARN. In Section 3, the proposed local dynamic routing strategy is described in detail. The simulation results and discussions are given in Section 4. The paper is concluded in the last section.

2. Air route network model and assumptions

The ARN is modeled as a time–space network. In the space domain, the height is ignored and the ARN is embedded in a two-dimensional Euclidean space. It consists of airports and ARWs with stationary geographical locations and ARSs which connect airports and ARWs. Naturally, the airports and ARWs are represented by nodes and the ARSs are featured by edges in the network model.[10] In this paper, N, P and W denote the set of all the nodes, the set of airports and the set of ARWs, respectively, where $N = P \cup W$. We denote by n_i the ith node in N, p_i the ith airport in P and w_i the ith ARW in W. The set of ARSs is denoted by E, and $e_{ij} \subset E$ denotes the ARS connecting nodes n_i and n_j. Notice that e_{ij} and e_{ji} are treated as two ARSs.

In the time domain, we divide the time axis into time slots denoted by τ. At the end of each time slot, we record the state of the ARN, including the flights generated during this time slot, the total number of flights living in the ARN, the locations, the destinations and the next step ARWs of all the flights.

There are several assumptions related to the characters of nodes and edges given below.

(1) The nodes stand for airports are treated as both generators and routers for generating and delivering flights, and the nodes stand for ARWs are treated as routers only for delivering flights.
(2) The delivering ability of each ARW is limited and is proportional to the degree of the ARW. It is denoted by $D_i = \alpha k_i$, where α is a coefficient and k_i is the degree of w_i.
(3) Considering the aircraft separation assurance, each ARS has a distance related capacity, which represents the maximum number of en-route flights on the ARS. It is denoted by $C_{ij} = \beta\lceil d_{ij}/\Delta d\rceil$, where $\lceil\bullet\rceil$ is the ceiling function, β a coefficient, Δd the minimum aircraft separation distance and d_{ij} the length of e_{ij}.
(4) Since we focus on the performance of wide- area ARN other than that of the terminal area, we assume that the delivering ability of each airport can satisfy the requirement from the rest part of the network. This means that the delivering ability of each airport is not limited.

There are still several assumptions related to the dynamic behavior of the ARN given below.