A Weighted Graph-Based Handover Strategy for Aeronautical Traffic in LEO SatCom Networks

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***Abstract*—With the development of space-air-ground integrated network (SAGIN), the Low Earth Orbit Satellite Communication (LEO SatCom) network has great potential to provide high rate communication services for aeronautical traffic. To overcome the frequency handovers between aircraft and LEO satellites, we generated a global aeronautical traffic demand map and utilized the graph-based handover (GBH) framework and the multi-attribute decision making (MADM) algorithm jointly to optimize the overall throughput. Moreover, we further propose a new parameter, called channel reservation order (CRO), for MADM algorithm. Simulation results indicate our strategy improves the performance in terms of overall throughput and access failure probability.**

***Index Terms*—Space-air-ground integrated network, low earth orbit satellite communication network, aeronautical traffic, satellites handover.**

I. Introduction

DESPITE the significant development of the 5G networks, the limited coverage and inflexible deployment remain critical challenges for further advancement. On the one hand, the problem of lacking network coverage still exists in some terrains such as deserts, mountains, and seas. On the other hand, the terrestrial networks fail to provide high rate communication services for aeronautical traffic. In such a case, the space-air-ground integrated network (SAGIN) [1], [2] and the satellite–terrestrial integrated network (STIN) [3], [4] have recently aroused a lot of research interest, wherein the Low Earth Orbit Satellite Communication (LEO SatCom) network plays an important role. Meanwhile, the accelerated process of building LEO mega-constellations [5] has launched a new upsurge of research for LEO SatCom networks. However, the topology of the LEO constellation changes constantly due to its rapid motion, which results in frequent handovers and further affects the quality of service (QoS). For LEO satellites, there are three types of handover, i.e., inter-satellite link (ISL) handover, handover between satellites and spotbeam handover [6]. Approaches for spotbeam handover are relatively abundant, and ISL handover is an inter-satellite routing problem, which is beyond the scope of this letter. Consequently, we focus on the handover between satellites, referred to as satellites handover, in the following.

Different approaches are utilized to research LEO SatCom network. A learning-based approach was proposed in [7] to solve the computing offloading problem. In [8], the authors established a directed acyclic graph to handle the transmission schedule. In some existing literature on satellites handover research, the graph-based handover (GBH) framework, proposed in [9], is one of the most widely used approaches. Nevertheless, the prediction time in [9] is undefined, which may incur poor performance or complex calculations. As for most of the researches on satellites handover with the GBH framework [10], [11], they transformed the determination of prediction time into the updates of the graph, i.e., converting random traffic time that is also the prediction time to periodic updates of the GBH framework. However, [10], [11] failed to seek out a proper type of traffic for the GBH framework, such as aeronautical traffic.

One of the currently largest growing sources of growth for LEO SatCom industry is the provision of services to passengers on aircraft [12]. To get the realistic aeronautical traffic demand, we transfer the world's largest source of unfiltered flight data website—Automatic Dependent Surveillance-Broadcast (ADS-B) Exchange for flight snapshot data of global aircraft every five seconds. Then we generate a traffic demand map in Section II-A, from which we can see that the aeronautical traffic is mainly concentrated in Europe, America and Southeast Asia, where the average traffic volume is about 2000 Mbps every 10,000 km^2 and can reach 9000 Mbps in some regions. In short, almost a quarter of the earth's surface is covered by aeronautical traffic, demonstrating the urgent demand for LEO SatCom network.

Hence, we focus on the communication between aircraft and LEO Satellites. The main work of this letter is as follows: We first generate a statistics-based map to analyze the global aeronautical traffic demand. To the best of our knowledge, this is the first work considering the realistic aeronautical traffic demand to improve the QoS for the users on aircraft. Next, we consider a joint handover prediction model of the

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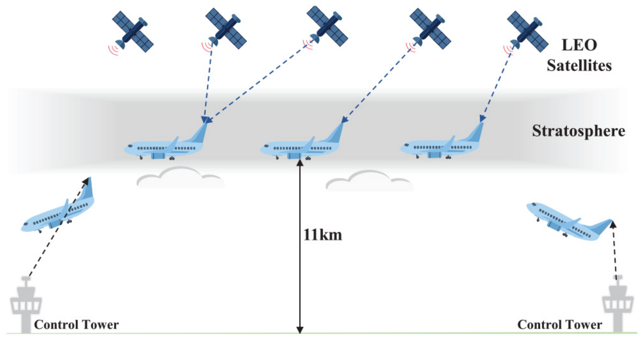

Fig. 1. Communication between aircraft and LEO SatCom network.

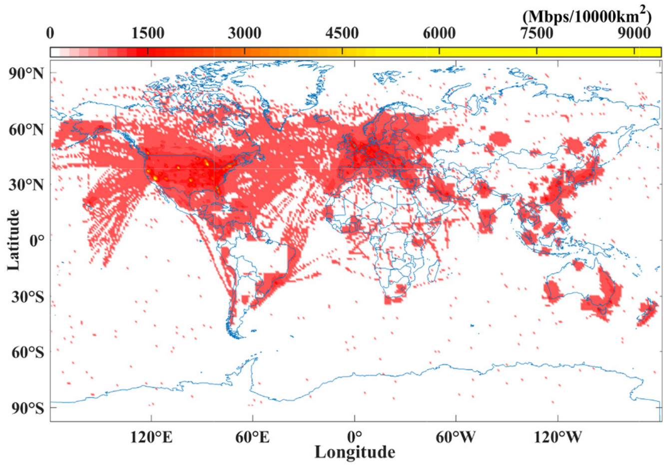

Fig. 2. Global aeronautical traffic demand map based on ADS-B data.

GBH framework and an improved MADM algorithm to solve the satellites handover problem. Moreover, we propose a new parameter, channel reservation order (CRO), for the MADM algorithms, which further improves the performance in terms of overall throughput and access failure probability.

II. System Model and Problem Formulation

Generally, aircraft communicate only with the control tower when take-off and landing, and will get satellite information from the control tower at the take-off stage, as in Fig. 1. Accordingly, we only consider the aircraft flying in the stratosphere where they cannot access the terrestrial network, and we suppose all passengers will access the LEO SatCom network via the airborne satellite transceivers. Additionally, aircraft will not change routes with an average altitude of 11 km.

A. Traffic Model Based on Aeronautical Traffic Demand

To get the actual traffic demand, we transfer ADS-B exchange for global aircraft' flight snapshot data, including aircraft type, route, velocity, and other messages. Suppose the load factor of each aircraft is 0.7 and the average traffic demand of each passenger onboard is 0.5Mbps, then we generate the global aeronautical traffic demand in Fig. 2.

Once the destination is decided, the aircraft's route is fixed. Meanwhile, we divide the world into 180 × 360 grids by latitude and longitude, and the routes are divided into several parts in each grid at the same time. Then we can regard the mobile aeronautical traffic as static with traffic density $D(p)$ in each grid p, where the density $D(p)$ of grid p can be its traffic demand in Fig. 2 after normalization.

In this way, we can obtain a simulation traffic model according to what is shown in Fig. 2.

B. Satellite Resources and Transmission Model

We assume that the LEO satellite constellation can cover the earth seamlessly except the poles where aircraft do not fly over. The adjacent satellites are polarized in different ways to avoid co-frequency interference. Hence, all satellites in the constellation can share the same bandwidth B, and we divide each satellite's resource equally into N channels to serve N aircraft at most. Thus, the transmission bandwidth for aircraft i is $B_i = B/N$. Furthermore, the ISL in the constellation is robust enough, and spot-beam handover is instantaneous, with the failure probability equal to 0.

Since the uplink and downlink are symmetrical, we take the downlink of satellite s for example in this letter. The received $\mathrm{SNR}_{s,i}$ (signal-noise ratio) at the airborne satellite receiver of aircraft i is given as:

$$\mathrm{SNR}_{s,i} = (\mathrm{EIRP})_s + (G/T)_i - 10\lg B_i - k_\mathrm{B} - \mathrm{LOSS}, \quad (1)$$

where $(\mathrm{EIRP})_s$ is the equivalent isotropically radiated power of satellite s. $(G/T)_i$ and B_i are the airborne antenna quality factor and the transmission bandwidth of aircraft i, respectively. k_B is the Boltzmann constant. LOSS mainly includes free space loss L_FS, atmospheric attenuation L_A and receiver feeder loss L_RF, given by

$$\mathrm{LOSS} = L_\mathrm{FS} + L_\mathrm{A} + L_\mathrm{RF}. \quad (2)$$

In (2), L_FS is the main loss for satellite-aircraft signals, satisfying

$$L_\mathrm{FS} = 20\lg(F) + 20\lg\left(D_{s,i}\right) + 32.4, \quad (3)$$

where F is the carrier frequency in the Ka-band. $D_{s,i}$, denoting the distance between satellite s and aircraft i, can be acquired by aircraft's ADS-B data and satellite Two-Line orbital Element (TLE).

L_A is Atmospheric attenuation [13] given as:

$$L_\mathrm{A} = L_\mathrm{rain} + L_\mathrm{cloud} + L_\mathrm{watervapor} + L_\mathrm{oxygen} + L_\mathrm{scintillation}. \quad (4)$$

Actually, L_cloud and L_rain are ignorable, because of the aircraft's higher altitude than clouds and the tendency to avoid hazardous meteorological events for obvious safety issues, respectively. Based on the simulation results in [12], L_A mainly affects aircraft at the take-off and landing stage and is less than 0.5 dB in the stratosphere.

Besides, L_RF in (2) is invariable for simplicity. The value of $L_\mathrm{A} + L_\mathrm{RF}$ is shown in TABLE I.

C. Throughput

With (1), we can obtain the ideal transmission rate $R_{s,i}$ between satellite s and aircraft i:

$$R_{s,i} = B_i \log_2(1 + \mathrm{SNR}_{s,i}), \quad (5)$$

TABLE I
MAIN SIMULATION PARAMETERS

Parameters	Value
Orbit Altitude	1000 km
T_p	30 s
Frequency	28 GHz(Ka)
Bandwidth	500 MHz
Channel Number	100
G/T	10 dB/K
$L_{\mathrm{A}} + L_{\mathrm{RF}}$	0.5 dB

where $= B_i$ is the transmission bandwidth in Section II-B, $\mathrm{SNR}_{s,i}$ is given in (1).

Furthermore, the throughput $U_i(S_i)$ of aircraft *i* is:

$$U_i = \frac{\sum_{s \in S_i} R_{s,i} \times T_{s,i}}{T_i}, \tag{6}$$

where S_i is the set of all the satellites reserved by aircraft *i*, T_i is the traffic time for *i*, $T_{s,i}$ is the service time of satellite *s* for *i*.

Let *I* be the set of all aircraft, then the overall throughput *U* is given as:

$$U = \sum_{i \in I} U_i. \tag{7}$$

D. Problem Formulation

The purpose of our work is to select the optimal LEO satellites S_i for each aircraft $i \in I$, which maximize the overall throughput *U*, so the optimization problem is given as:

$$\begin{aligned} \max_{S_i \subseteq A} \quad U &= \sum_{i \in I} U_i \\ &= \sum_{i \in I} \frac{\sum_{s \in S_i} R_{s,i} \times T_{s,i}}{T_i} \\ \text{s.t.} \quad l_s &< L, s \in S_i, \end{aligned} \tag{8}$$

where *A* is the set of all the LEO satellites in the constellation.

Given the quantities of satellites and aircraft, large amounts of complex processing will be produced when obtaining S_i with traditional mathematics. Therefore, we construct an unweighted digraph with the coverage information, and use the MADM algorithm to evaluate the candidate satellites. Then we can obtain edge weights in the digraph with the results of MADM algorithm. Finally, we adopt the Dijkstra algorithm to select the shortest path in the digraph, which is also our optimal satellites S_i. The details will be given in Section III.

III. Joint Handover Strategy Based on GBH Framework and Improved MADM Algorithm

A. Handover Prediction With GBH Framework

As shown in Fig. 3a, suppose that an aircraft's route in the time interval $[T_1,\ T_2]$ is covered by satellites A-G, then we can obtain the coverage time evolution diagram (CTED) at the top of Fig. 3a. Meanwhile, the satellites handovers are seamless, which only occur in the overlapping area covered by the satellites. We can abstract the CTED into a unweighted digraph by the method described in [9], as shown in Fig. 3b. On this basis, the easiest way to select S_i is using the Dijkstra algorithm to obtain the shortest path in the digraph; however, this can only minimize the handover times if not calculating the edge weights in advance.

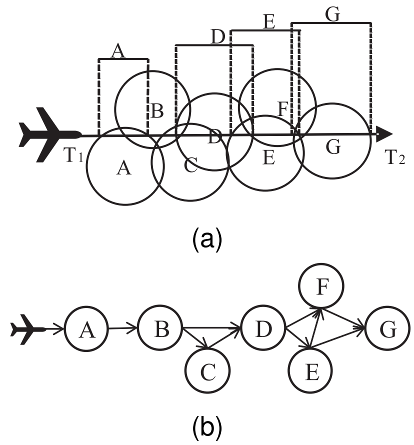

Fig. 3. Generation of the unweighted digraph, A-G are LEO satellites; (a) CTED of aircraft's route (only A,D,E,G are shown); (b) Digraph of the CTED.

B. Edge Weights and Improved MADM Algorithm

Many factors such as elevation angle, service time and available channel number can affect the performance of handover prediction; therefore, we employ MADM algorithms, such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy Process (AHP), to calculate the edge weights. Before employing the MADM algorithms, we need to set each attribute's weight based on its importance to the system. As a result, the MADM algorithm can be improved by calculating the time mean value of the overall throughput $U(x_a)$ when making a single-attribute decision, as in (9):

$$u_a = \lim_{T \to \infty} \frac{1}{T} \int_0^{\mathrm{T}} U(x_a, t)\, dt, \tag{9}$$

where, x_a is the *a*th one of all the attributes *X*.

Then, the weight w_a of the *a*th attribute is:

$$w_a = \frac{u_a}{\sum_{x_a \in X} u_a}, \tag{10}$$

and we can obtain the edge weights by normalizing the score of each satellite with the improved MADM algorithms.

C. Channel Reservation and CRO

After aircraft *i* finalizes S_i, these satellites should reserve the channel before arrival. If multiple aircraft select the same satellite channel, they will form a first-in-first-out (FIFO) queue based on their arrival time. Considering the GBH framework's characteristics and the channel reservation strategy, we propose a new parameter—CRO, which is the minimum order of all the FIFO queues Q_s of satellite *s*, i.e., if *s* has an unoccupied channel, CRO equals 1.

In order to improve the overall resource utilization, we consider the scenario where the user enables to occupy the reserved channel. The occupation process is illustrated in Fig. 4. Suppose that user *A* reserves the channel at t_0 and the handover will arrive at t_3; by prediction, user *B* will access

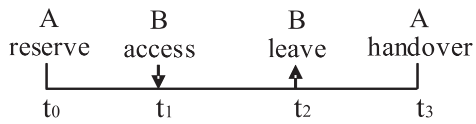

Fig. 4. Diagram of occupation condition, A and B are users.

Algorithm 1: Access Management

Input: Visible Satellites $S_{\text{vs}} \subseteq S_i$ at T_{access}.
Output: Update of the reservation queues, ΔQ.
Initialize: $T_{\text{wait}} \leftarrow 0$; $\Delta Q \leftarrow 0$;
while $T_{\text{wait}} < T_{\text{p}}$ **do**
  foreach $s \in S_{\text{vs}}$ **do**
    if $T_{\text{serve}} < T_{\text{arrival}}$ *or* $l_s < L$ **then**
      Success, break;
if *Success* **then**
  Handover prediction with GBH and MADM;
  Channel Reservation and obtain ΔQ;
return ΔQ.

the same channel at t_1 and leave at t_2. Then B can use the channel without affecting user A's handover. In other words, the occupation condition for B can be expressed as:

$$T_{\text{serve}} < T_{\text{arrival}}, \tag{11}$$

where $T_{\text{serve}} = t_2 - t_1$ is B's remaining service time and $T_{\text{arrival}} = t_3 - t_1$ is the remaining time before A's arrival, where t_1 is shown in Fig. 4.

D. Access and Handover Management

Before an aircraft *i* access the LEO SatCom network in the stratosphere, it should collects the information of all visible satellites S_{vs} from the control tower at the take-off stage. Then, aircraft *i* will traverse $s \in S_{\text{vs}}$ to check whether it meets the occupation condition (11) or has an idle channel successively until the waiting time $T_{\text{wait}} = t - T_{\text{access}}$ is greater than the patience time T_{p}, where *t* is the current moment and T_{access} is the access moment. Once successful, it will employ the improved MADM algorithm and the GBH framework to calculate the edge weights and conduct handover prediction. Finally, aircraft *i* will determine its handover target S_i, and these satellites should compute ΔQ, which is the update of the reservation queues; then the FIFO queues Q will get updated with ΔQ. The whole access process is shown in Algorithm 1.

When a new handover of aircraft *i* arrives, it checks whether the reserved queue Q's size equals one (i.e., only itself) at first. If not, aircraft *i* will search the channel that could be occupied or is idle. If neither, the handover will fail, and all the channel queues Q_i reserved by aircraft *i* will get updated, as in Algorithm 2.

IV. Simulation and Analysis

A. Simulation Setup

To cover as much of the area where aeronautical traffic is as possible, we build a Walker Delta constellation in our simulation software, and the earth's rotation is also taken into account. We only choose the southeast coast of China (110° ∼ 130° E, 10° ∼ 30° N) as our simulation area. Some other parameters are given in TABLE I. Meanwhile, ENTROPY TOPSIS and AHP methods are used for comparison.

Algorithm 2: Handover Management

Input: FIFO Queue Q of the Channel.
Output: Throughput Increasement ΔU_i and ΔQ.
Initialize: $T_{\text{wait}} \leftarrow 0$; $\Delta U_i \leftarrow 0$; $\Delta Q \leftarrow 0$;
while $T_{\text{wait}} < T_{\text{p}}$ **do**
  if *Size of* $Q = 1$ **then**
    Success;
  else
    if $T_{\text{serve}} < T_{\text{arrival}}$ *or* $l_s < L$ **then**
      Success;
if *Success* **then**
  Calculate ΔU_i with (5)(6);
else
  Update all FIFO queues Q_i reserved by *i*; Obtain ΔQ;
return ΔU_i and ΔQ.

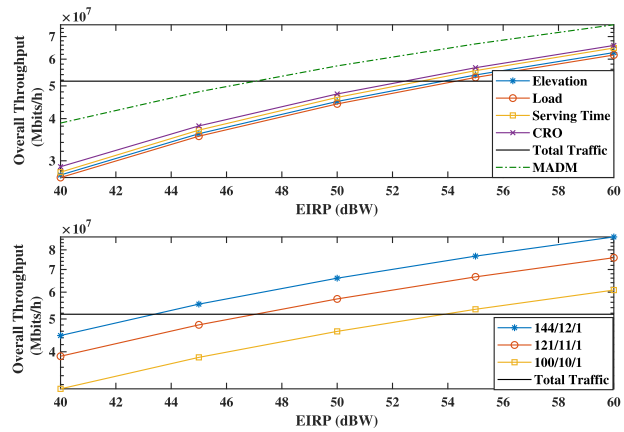

Fig. 5. Effect of LEO constellation's size with improved MADM algorithm; Effect of each attribute with walker configuration: 121/11/1.

B. Simulation Results

In our simulation scenario, the handover blocking rate is almost 0, which is the advantage of the GBH framework joint with the improved MADM algorithm. It avoids aircraft selecting satellites with too many loads so that the load is well-balanced and the handover will succeed with the maximum probability. However, access failures still occur when the satellite's load reaches the limit, which is the price of ensuring successful handovers.

In Fig. 5, we simulate the performance when each attribute makes decisions individually. The performance of MADM is much better than that of the four attributes, which is about 5 dBW for EIRP. Moreover, the parameter Load (i.e., available channel number) is the smallest due to the excellent balance obtained by our handover prediction framework, and CRO has the best performance, the detail is shown in Fig. 6. Fig. 5 also shows the effect of the LEO constellation's size. When satellites' number increase by 20, the EIRP will gain about 5 dBW. However, the award will be minor if we keep adding satellites.

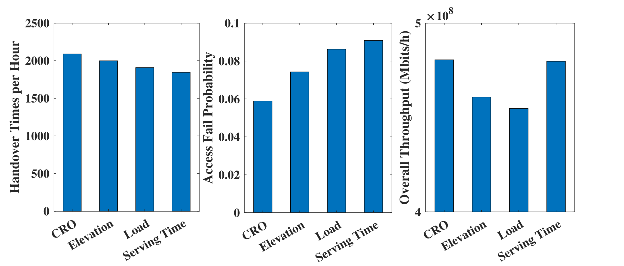

Fig. 6. Performance of CRO, Elevation, Load and Serving Time, EIRP: 50 dBW, Walker Configuration: 121/11/1.

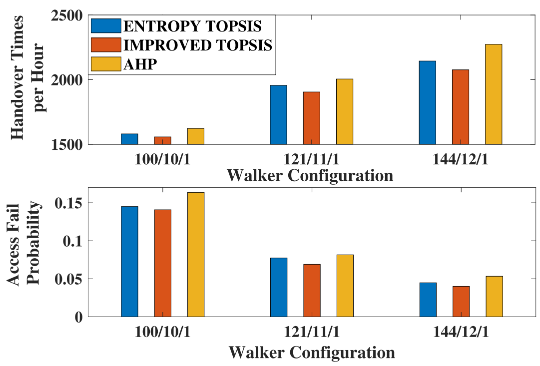

Fig. 7. Performance of MADM algorithms for handover, EIRP: 50 dBW; Performance of MADM algorithms for access, EIRP: 50 dBW.

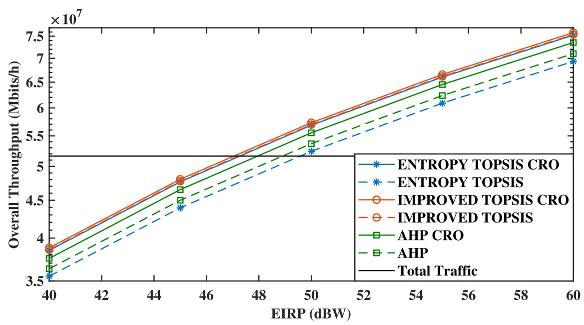

Fig. 8. Performance of MADM algorithms and CRO, Walker Configuration: 121/11/1.

Fig. 6 shows the detailed performances of the four parameters: CRO, Elevation, Load and Serving Time. We can see that CRO improves the overall throughput by reducing the probability of access failure, but it increases the handover frequency. The reason is that CRO does a great job of balancing the load by allocating more valuable handovers. Although the parameter Service Time does not significantly reduce access failure probability, it still improves the overall throughput close to CRO. Unlike CRO, it does not balance the system load, but increases the link's lifetime to reduce the throughput loss caused by handover failure.

Fig. 7 shows the detailed performances of the three MADM algorithms and three different constellation sizes. With the increase of satellites, the aircraft will have more handover targets, which can bring more handovers but make the load more balanced at the same time. Meanwhile, our improved MADM algorithm performs better both in handover frequency and access failure probability than AHP and Entropy TOPSIS.

In Fig. 8, the overall throughput of the improved TOPSIS algorithm meets the total traffic volume when EIRP reaches about 47.5 dBW, which is better than the traditional algorithms. Moreover, all three MADM algorithms' performance is improved with the parameter CRO considered, especially Entropy TOPSIS, which is almost 3dBW for EIRP.

V. Conclusion

This letter focuses on the handover strategy to provide high rate communication services for aeronautical traffic, one of the LEO SatCom network's application scenarios. We first analyzed the global aeronautical traffic demand by statistics data. Based on the GBH framework and an improved MADM algorithm, we employed a joint handover prediction model to solve the handover problem between aircraft and satellites. Then, We proposed a new parameter, CRO, for the MADM algorithms, and its improvement on overall throughput was verified with simulation in the southeast coastal area of China. The simulation results indicated that the improved MADM algorithm performs better than traditional ones. Besides, we explored the effect of the LEO constellation's size on the overall throughput, which could be used for reference in building LEO mega-constellation. In future work, we will extend our traffic model with maritime traffic and further design the distributed decision-making strategy in our model.

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