Analysis of the Chinese air route network as a complex network*

Cai Kai-Quan(蔡开泉), Zhang Jun(张 军),
Du Wen-Bo(杜文博), and Cao Xian-Bin(曹先彬)†

School of Electronic and Information Engineering, Beihang University, Beijing 100083, *China*

(Received 24 August 2010; revised manuscript received 13 October 2011)

The air route network, which supports all the flight activities of the civil aviation, is the most fundamental infrastructure of air traffic management system. In this paper, we study the Chinese air route network (CARN) within the framework of complex networks. We find that CARN is a geographical network possessing exponential degree distribution, low clustering coefficient, large shortest path length and exponential spatial distance distribution that is obviously different from that of the Chinese airport network (CAN). Besides, via investigating the flight data from 2002 to 2010, we demonstrate that the topology structure of CARN is homogeneous, howbeit the distribution of flight flow on CARN is rather heterogeneous. In addition, the traffic on CARN keeps growing in an exponential form and the increasing speed of west China is remarkably larger than that of east China. Our work will be helpful to better understand Chinese air traffic systems.

Keywords: complex network, Chinese air route network, air transportation

PACS: 89.75.–k, 89.75.Fb, 89.40.Da, 89.40.Dd **DOI:** 10.1088/1674-1056/21/2/028903

1. Introduction

With the rapid development of global economy, the transport of goods and people is becoming more and more frequent than ever before. During this process the contribution of airway is somewhat small compared with that of the traditional railway and roadway, whereas it plays an irreplaceable role in the modern society and keeps faster increasing in the past years. For example, the air traffic of China grows at the speed of 15% per year from 2005 to 2010, while the railway traffic increases at the speed around 4%.[1] Moreover, the prosperous aviation industry also draws much attention from different communities. Most notably, one of interesting and important research fields is to analyse the infrastructure of aviation industry within the framework of complex network theory.[2,3]

Many real systems in nature and human societies can be abstracted as networks,[4−6] where the entities of the system can be represented by the vertices and the interactions between entities can be denoted by the edges.[7−10] These real networks are usually quite diverse, which will be supported by some detailed examples. For instance, the most famous social network site Facebook makes more than 600 million people connected, while 79 airports linked by 228 airlines bear all the air traffic demand of India. Along with the flourishing development of complex network theory, the discovery of the exciting small-world network model[11] and scale-free network model[12] proposed at the end of the last century makes it reach a tip of the iceberg. Since then people become to realize that real networks are neither regular lattices nor random graphs, but complex networks with small-world property and power-law degree distribution. For a recent review, one can refer to Refs. [13]–[15].

Looking through the majority of previous research about infrastructure networks in air transportation, we find that the airline network attracts the most attention, where airports are regarded as vertices and airlines as edges. Barrat *et al.* investigated the connection intensity of the world-wide airport network (WAN) and found the correlations between weighted quantities and topology following a power-law behaviour.[16,17] Guimera *et al.* manifested that the airports with most airlines in WAN were not necessarily the most central nodes, which means critical lo-

*Project supported by the National Basic Research Program of China (Grant No. 2011CB707004), the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (Grant No. 60921001), the National Key Technologies R & D Program of China (Grant No. 2011BAH24B02), and the Fundamental Research Funds for the Central Universities.

†Corresponding author. E-mail: xbcao@buaa.edu.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

cations might not coincide with highly-connected hubs in the infrastructures of air traffic systems.[18,19] Besides, the national airline networks, such as the airline network of America,[20] China,[21−23], Brazil,[24] and India,[25] are also extensively studied. It is found that the national airline networks can exhibit different properties including disassortative mixing, two-regime power-law degree distribution, frequent dynamic switchings, exponential traffic increasing and so on. Hence, it will be very meaningful to explore other new aspects of air transportation.

In this paper, we will investigate another kind of network in air traffic systems, namely, the air route network (ARN). ARN is the backbone of national airspace and will affect the flight distance and operational efficiency of the air transportation system. In the air transportation, all the flights will receive the strict constraints of ARN. Furthermore, most of the air traffic management activities, such as aircraft separation assurance, flights conflicts resolution, air traffic flow control and navigation infrastructure constructions are centering on the ARN. Here, we will focus on the Chinese air route network (CARN).

The paper is organized as follows. In Section 2, we give a simple introduction of air route network and present the statistical analysis of CARN topology via comparing it with the Chinese airline network (CAN). The traffic flow on CARN is comprehensively investigated in Section 3. The paper is concluded in the last section.

2. Topological properties of CARN

First, let us introduce some basic elements in ARN. As shown in Fig. 1, the dotted line represents the airline between Beijing and Shanghai, which is the one of the busiest airlines in China, while the air route segments (ARSs) are depicted by the solid line and connected by a series of air route waypoints (ARWs). An ARW is a navigation marker whose longitude and latitude coordinates are determined by the ground navaids and keep the pilots informed about the desired track and heading direction of the aircraft. With its help, pilots can have exact positions from the ground navaids to keep on the right track. Since the performance criterion of navaids required by air navigation is quite strict (e.g., the signal coverage must be ideal, the signal strength call for being sufficient and the power supply demands to be enough stable), the geographical condition plays a crucial role in the deployment of ground navaids. Therefore, ARWs are seldom located in the places where the navigation signals cannot freely propagate, such as the valleys and plateaus. Based on these considerations, flights in reality will not directly fly from departure airport to arrival airport, but fly along the ARWs. Naturally, the ARWs represented by vertices and the ARSs featured by edges structure the air route network.

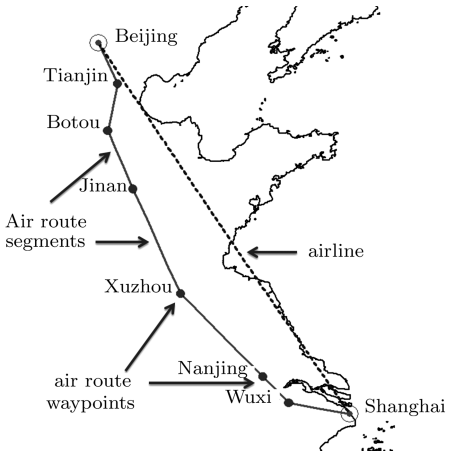


Fig. 1. An illustration of airline and air route between two largest cities in China: Beijing and Shanghai. The air route waypoint (ARW) is represented by the blue circle, the air route segment (ARS) is denoted by the red solid line and the airline is shown as the blue dotted straight line. The flights in reality will not directly fly from one airport to another, but fly along the ARWs.

Next, it will become interesting to investigate the topological properties of CARN. In order to satisfy the need of comparison, CAN is also studied. The latest data of CARN and CAN are provided by the Air Traffic Management Bureau (ATMB) of China. Figures 2(a) and 2(b) give an intuitionistic representation of CAN and CARN respectively. One can see that CAN is remarkably more heterogeneous than CARN: the degree of top 3 airports in China, namely, Beijing Capital Airport, Shanghai Pudong Airport and Guangzhou Baiyun Airport, is 100, 85, and 81, while the largest degree in CARN is only 11 (Pudong, Pingzhou and Kuqa in Fig. 2(b)). In CAN, if there exists traffic demand between airport A and airport B, there will be a direct airline connecting A and B. However, more constraints are considered in CARN: ARWs cannot be deployed in the rough topography, the coverage radius of ARWs is limited, ARSs should cover all airlines and hub ARWs are unacceptable to avoid possible traffic congestion and flight conflicts, all these will decrease the degree of vertices to a large extent.

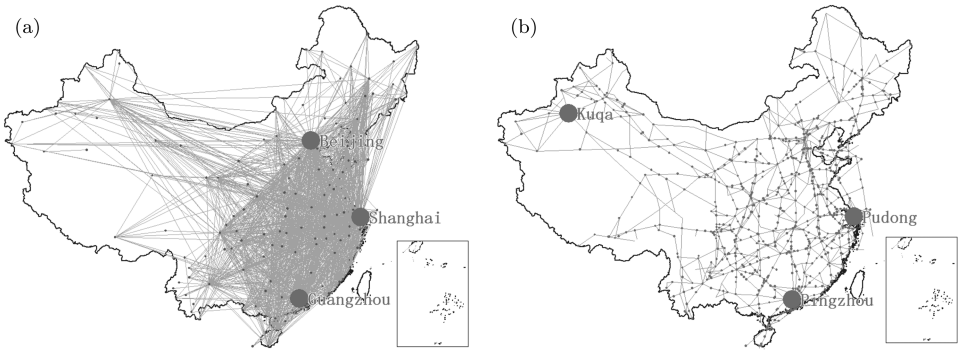


Fig. 2. (a) The Chinese airport network (CAN) contains 147 airports and 1055 airlines. The top 3 airports, namely Beijing, Shanghai and Guangzhou, are emphasized. (b) The Chinese air route network (CARN) contains 1013 ARWs and 1586 ARSs. The top 3 ARWs, namely Pudong, Pingzhou, and Kuqa, are emphasized.

Table 1. A comparison between basic network parameters of CAN and CARN.

	CAN	CARN
Nodes	147	1013
Edges	1055	1586
Average degree	14.35	3.13
Average shortest path length	2.20	14.08
Diameter	4	39
Mixing coefficient	–0.15	–0.14
Clustering coefficient	0.79	0.08
Longest edge/km	3379.22	638.06
Shortest edge/km	133.93	1.94

Table 1 briefly shows the comparison among some basic network parameters of CAN and CARN. First, CARN is sparser than CAN. CARN contains 1013 nodes, which is 7 times larger than that of CAN. However, the edges of CARN are only 1.5 times larger than that of CAN. The average degree of CARN is merely 3.13 while the average degree of CAN is 14.35. Secondly, CARN is less "small-world" than CAN. The average shortest path length and the network diameter of CAN are 2.20 and 4 respectively, indicating that most paths consist of about 2 flights and passengers can gain an arbitrary airport from an arbitrary departure airport in no more than 4 flights. Thus CAN is remarkably a typical "small-world" network. However, these two parameters of CARN (The average shortest path length is 14.08 and the network diameter is 39) are closer to those of the regular lattice. Thirdly, although both CARN and CAN own a negative mixing coefficient, the clustering coefficient of CARN is much smaller than that of CAN. Simultaneously, the negative mixing coefficient means large-degree nodes are more likely to link the small-degree nodes. Since the clustering coefficient represents the possibility of "a neighbour of node X's neighbour is also the neighbour of node X", large clustering coefficient indicates CAN is more compactly connected and small one implies CARN is less intense. Besides, we find that the geographical distance of CARN's edge is much shorter than that of CAN's edge: the longest edge of CAN is 3379.22 km while the longest edge of CARN is 638.06 km and the shortest edge of CAN is 133.93 km while the shortest edge of CARN is only 1.94 km. The longest airline of CAN is between Fuzhou Changle Airport and Urumqi Diwopu Airport which cuts across southeast China and northwest China 3379.22 km and the shortest airline is between Guangzhou Baiyun Airport and Shenzhen Huangtian Airport in the south China 133.93 km. The longest ARS of CARN (638.06 km) is the route segment between Kashgar and Kuqa which lies in the Xinjiang Uygur Autonomous Region of west China and the shortest ARS of CARN (1.94 km) is the route segment between ARGUK and Haiqing which is located in the territory of northeast China.

Figure 3 shows some topology parameters of CAN and CARN in detail. First, we focus on the situation of degree distribution, which is the most crucial feature of network. In Figs. 3(a) and 3(b), one can see that both the degree distributions of CAN and CARN follow exponential functions $P(X \geq k) \propto \mathrm{e}^{A \cdot k}$ and CARN is more homogeneous than CAN: $A = -2.02$ for CAN and $A = -25.4$ for CARN. (Previous works usually viewed CAN as a complex network with a two-regime power-law degree distribution.[21–23] For the latest data of CAN, however, the degree distribution can also be well fitted by an exponential function. The error of exponential fitting is quite low: $A = 2.02 \pm 0.04$). Besides, CAN has apparent negative degree–degree correlation (Fig. 3(c)) and negative degree–clustering correlation (Fig. 3(e)),

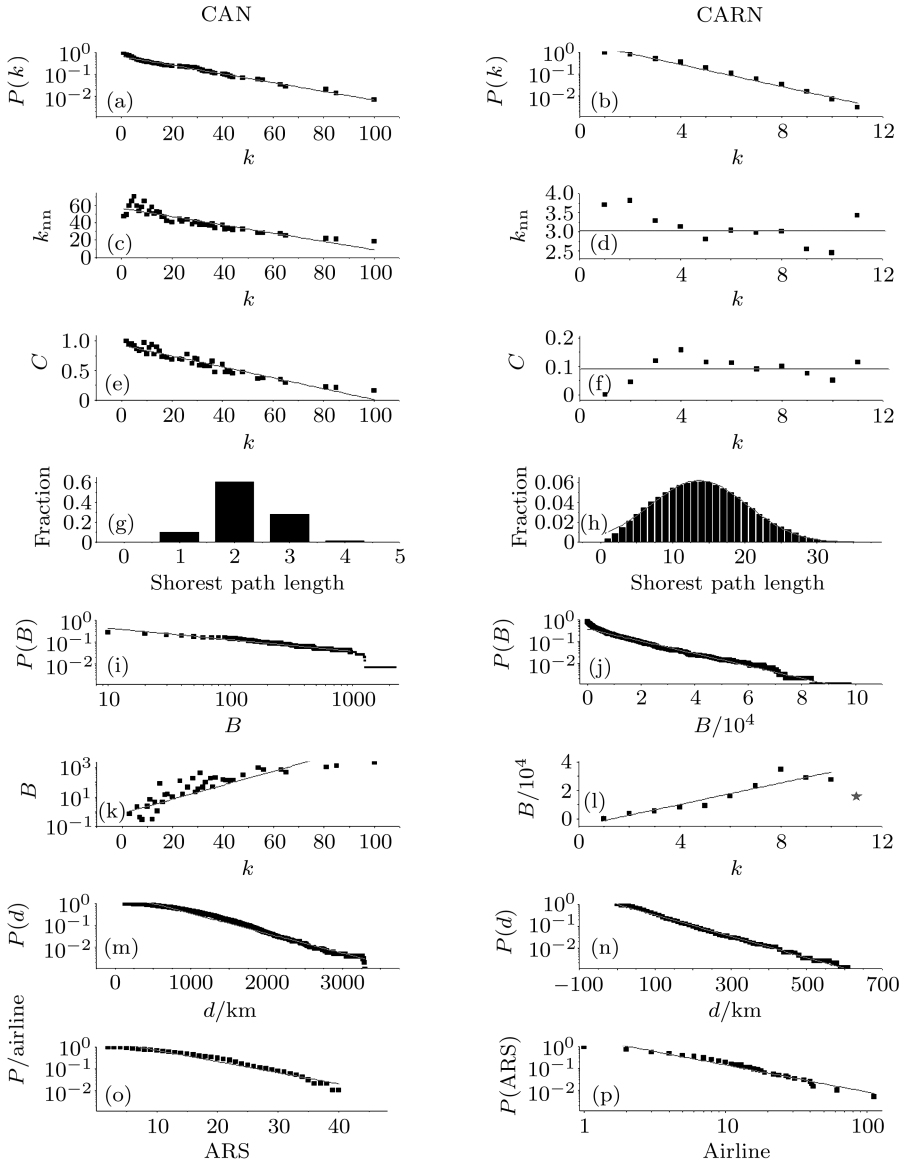


Fig. 3. A one-to-one comparison of some topology parameters of CAN and CARN (a) and (b) The accumulative degree distribution of CAN and CARN, (c) and (d) The degree–degree correlation of CAN and CARN. $k_{\rm nn}$ is the average degree of neighbours. (e) and (f) The degree–clustering correlation of CAN and CARN. C is the clustering coefficient. (g) and (h) The distribution of shortest path length of CAN and CARN. (i) and (j) The betweenness distribution of CAN and CARN. B is the betweenness. (k) and (l) The degree–betweenness correlation of CAN and CARN. (m) and (n) The distribution of geographical distance of CAN and CARN. d is the geographical distance. (o) and (p) the ARS-airline correlation and the airline–ARS correlation.

indicating low-degree nodes have large-degree neighbours and higher clustering coefficient. While for CARN, there exist no obvious degree–degree or degree–clustering correlations. The average degree of neighbours, named by $k_{\rm nn}$, is around 3.0 (Fig. 3(d)) and the clustering coefficient is around 0.08 (Fig. 3(f)), un-relating to nodes' degree. Second, we investigate the shortest path length that is specially important for transportation systems. For CAN, over 98% paths consist of no more than 3 flights (Fig. 3(g)). While for CARN, the distribution of shortest path length can be fitted as a normal distribution (Fig. 3(h)). In addition, betweenness is another important parameter for transport process on networks. One can find that the distribution of betweenness is quite different for CAN and CARN: CAN exhibits a power-law distribution (Fig. 3(i)) while CARN is an exponential distribution (Fig. 3(j)). The degree–betweenness correlation, which is crucial for the performance of a networked traffic system, is also studied. We can see that both CAN and CARN have positive degree–betweenness correlations: exponential for CAN (Fig. 3(k)) and lin-

ear for CARN (Fig. 3(l)), indicating large-degree nodes may bear more traffic load in CAN. Interestingly, it is worth while noting that the largest degree nodes of CARN apparently deviate from the linear fitting function. The 3 nodes with $k = 11$ are the ARWs: Pudong, Pingzhou and Kuqa, which are located near the border of CARN (Fig. 2(b)). Thus the number of shortest paths passing through them is quite limited even if they have a large degree. Lastly, since CAN and CARN are both transportation networks possessing geographical meanings, the distribution of edge's spatial distance is also presented. One can find that both of them have exponential edge distance distributions (Fig. 3(m) and Fig. 3(n)) and the geographical distance of airline is remarkably longer than ARS: over 90% airlines are longer than 400 km and only 8% ARSs are longer than 200 km. This comparison reflects that one airline consists of several ARSs. As figure 3(o) features, airlines consist of $2 \sim 40$ ARSs and the distribution of the number of ARSs that an airline owns follows an exponential function. On the other hand, one ARS can also be used by several airlines. As shown in Fig. 3(p), the distribution of the number of airlines where an ARS is used follows a power-law distribution, indicating that only a few ARSs are highly multi-used while most ARSs are just used by several airlines.

From the above discussion, we know that CARN is a homogeneous network with an exponential degree distribution, a low clustering coefficient, a large shortest path length, an exponential betweenness distribution, a linear betweenness–degree correlation and an exponential spatial distance distribution. Then we will investigate the traffic flow on CARN.

3. Traffic on CARN

The traffic data of CARN used in this section are obtained from 17 timetables provided by the Air Traffic Management Bureau (ATMB) of China from 2002 to 2010 (2 timetables for years $2003 \sim 2010$ and 1 timetable for the second half of 2002). Since the timetables only contain the scheduled flights, the data are not perfectly consistent with real flights due to the influence of weather or emergencies.

Figure 4(a) shows the distribution of node strength S, where S is traffic flow (defined as the number of flights) passing through an ARW within one week. One can find that although the topology of CARN is quite homogeneous, the traffic on CARN is rather heterogeneous (the distribution of S is 4 orders of magnitude). And the distribution follows an exponential function. Figure 4(b) features the degree–strength correlation of CARN. One can

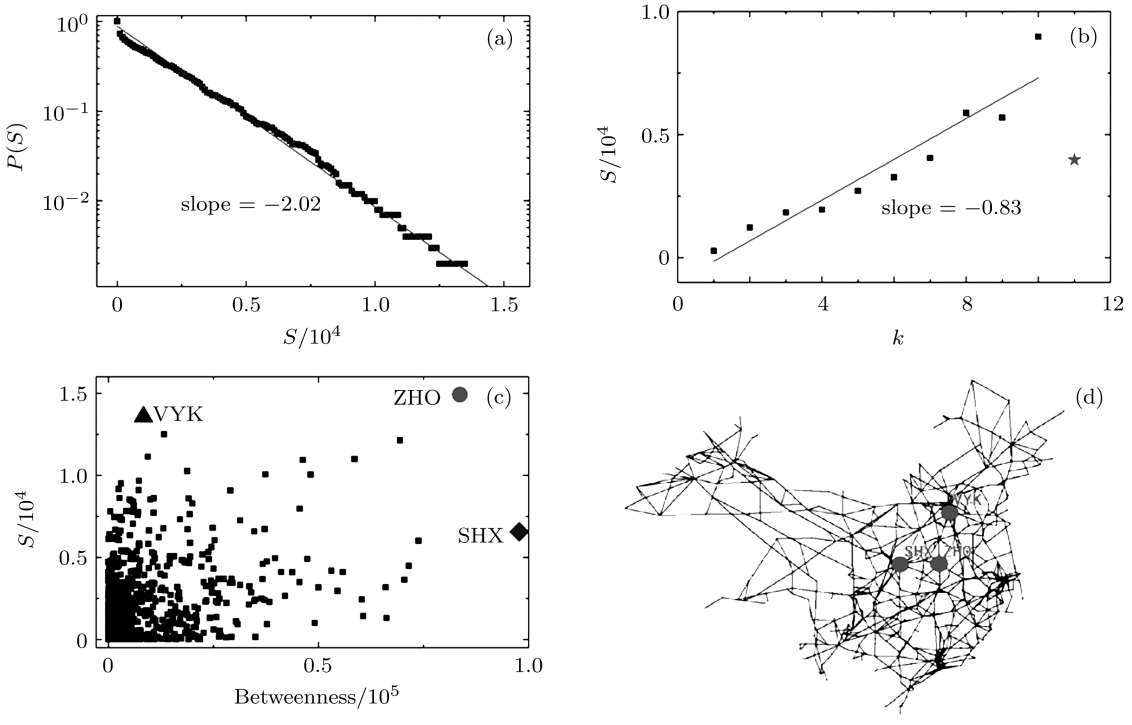


Fig. 4. (a) The exponential distribution of node strength of CARN. (b) The linear degree–strength correlation of CARN. (c) The betweenness–strength correlation of CARN. (d) Some significant ARWs in CARN.

find that the relationship between degree and node strength can be well linearly fitted, except for $k = 11$. While the strengths of 3 nodes with $k = 11$ (Pudong, Pingzhou and Kuqa) are 7156, 2760, 1688, respectively. At a first glance, we discover that the traffic flow of Pingzhou and Kuqa seems incompatibly low. With respect to Kuqa the low traffic flow is mainly induced by the geographical position. Since it is located in the west border of west China where the air traffic is not busy. And naturally its strength cannot be large. While for Pingzhou, it is located in the prosperous area around Guangzhou (one of China's most important cities), but is only planned to serve the regional flights. Therefore, the traffic strength of Pingzhou is likewise low. Moreover, figure 4(c) characterizes the relationship of betweenness and node strength. One can find that most ARWs are in the field of low betweenness and low strength ($0 <$ betweenness $< 2.5 \times 10^4$ and $0 < S < 5 \times 10^3$). In order to portray more conveniently, we specify several significant ARWs: ZHO (high betweenness and high strength), SHX (high betweenness and low strength), VYK (low betweenness and high strength). As revealed in Fig. 4(d), ZHO is located in the central China and it is also a hinge point between east–west airlines and south–north airlines. And thus ZHO is not only important in topology but also in air traffic flow. SHX is an important ARW connecting northwest China and southeast China. Since these airlines are not so busy, the traffic property of SHX is not as important as its topology property. Finally, VYK is in the terminal area of Beijing, which undertakes more than 13% air traffic flow in China. Although its degree and betweenness is considerably small, the traffic flow of VYK is only lower than ZHO.

Since the aviation industry of China has made a great miracle during the past decades, it is instructive to investigate the traffic evolution of CARN. As figure 5 shows, the traffic flow follows an exponential distribution for all years (Fig. 5(a)) and the total traffic flow increases in the exponential form (Fig. 5(b)). From the inset of Fig. 5(b), especially, we can find that the total traffic flow of the second half year of 2010 is 2.46 times as that of the second half year of 2002. Moreover, we discover the traffic development on CARN is significantly unbalanced. The increment of the traffic on traditional busy ARWs is much slower than the average speed. Take VYK (an important ARW near the Beijing Capital Airport, which bears 13.1% passengers and 13.7% cargos in the total air traffic of China) and Pudong (an important ARW near the Shanghai Pudong Airport, which bears 7.2% passengers and 28.6% cargos in the total air traffic of China) for example, the traffic passing by VYK (Pudong) of the second half year of 2010 is only $M(17) = 2.03(2.06)$ times as that of the second half year of 2002 (Fig. 5(c) and Fig. 5(d)). On the other side, the traffic of ARWs in west China increases at a higher speed: the traffic passing by Urumqi /Lasha of the second half year of 2010 is $M(17) = 3.78/3.48$ times as that of the second half year of 2002 (Fig. 5(e) and Fig. 5(f)). Interestingly, we also find that the traffic flow of these two western ARWs (Lasha and Urumqi) has remarkable seasonal fluctuations: the traffic flow of the second half year is unusually larger than that of the first half year. The main reason for

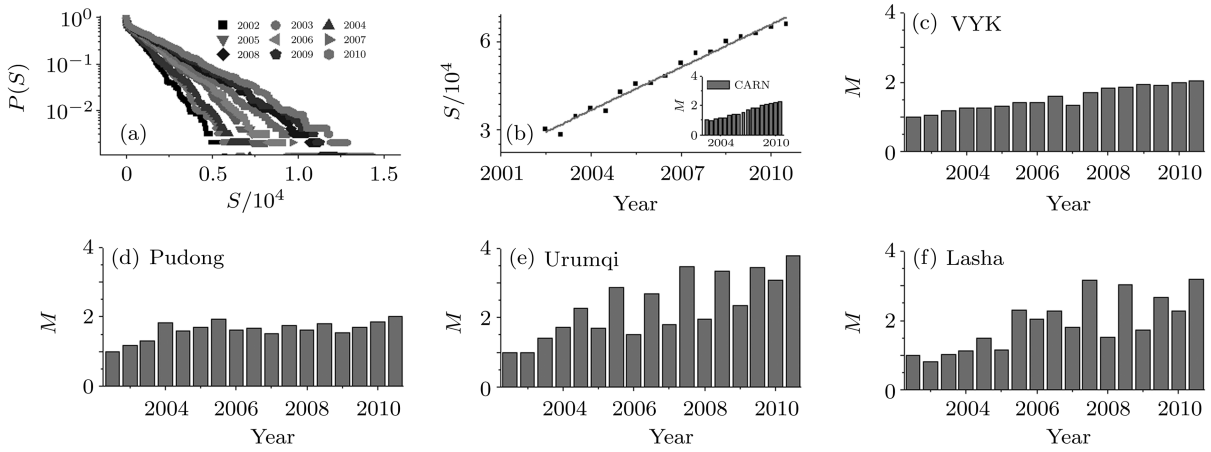


Fig. 5. (a) The distribution of node strength from year 2002 to year 2010. (b) The evolution of total traffic in CARN. (c)–(f) The evolution of traffic flow of four ARWs: VYK, Pudong, Urumqi, and Lasha. One can find $M(i)$ of Lasha and Urumqi is remarkably larger than that of VYK and Pudong. Here $M(i) = F(i)/F(1)$, where $F(i)$ is the traffic flow of the i-th timetable from the second half year of 2002 to the second half year of 2010 and $1 \leq i \leq 17$.

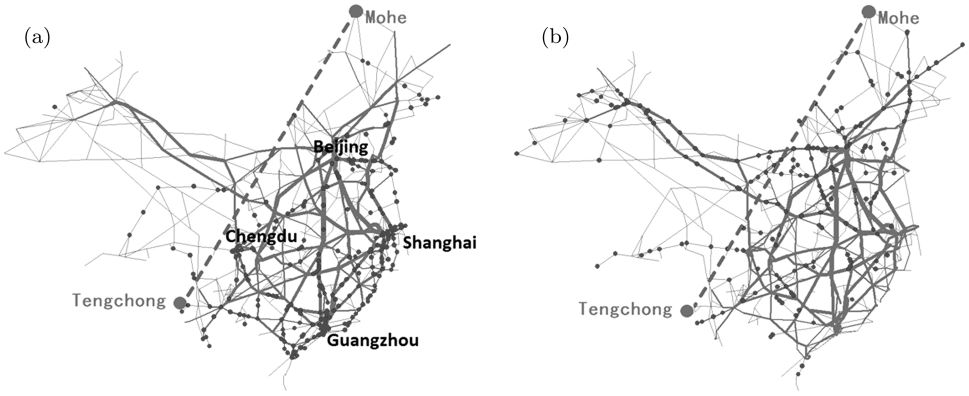


Fig. 6. (a) The ARWs with $M(17) < 2.46$. (b) The ARWs with $M(17) > 3$. The dotted line is the traditional separatrix of east China and west China.

this seasonal fluctuation is the unbalanced air traffic demand: both Lasha and Urumqi are tourist attractions and the busiest tourist season for them is autumn.

Lastly, figure 6 gives a detailed intuitionistic picture of the unbalanced development of CARN. Figure 6(a) shows the slow-growing ARWs with $M(17) < 2.46$. One can find most slow-growing ARWs are located in east China, especially in the airspace around four first-tier cities: Beijing, Shanghai, Guangzhou and Chengdu. While figure 6(b) features the fast-growing ARWs with $M(17) > 3.00$. It is found that most fast-growing ARWs are located in west China and second-tier cities, which indicates that the air traffic of developed region has already been in the stable phase while that of less developed region is entering into the accelerated growth phase.

4. Conclusion

In summary, we have analysed the fundamental infrastructures of air transportation in China within the framework of complex network theory. The so-called Chinese Air Route Network (CARN) has been constructed by associating node to ARW and edge to ARS. Interestingly, it is found that the topology structure of CARN is apparently more homogeneous than the Chinese airport network (CAN). However, by examining the scheduled flights on CARN, we find that the distribution of air traffic flow on CARN is rather heterogeneous with exponential strength distribution. Finally, through studying the traffic evolution of CARN, we also find that the traffic on CARN keeps growing in an exponential form and west China grows remarkably faster than east China. Our work is helpful for further understanding of Chinese air traffic system and it may shed some light on the optimal design of networked transportation systems.

References

[1] *Statistical Data on Civil Aviation of China 1992–2009* (Beijing: Chinese Civil Aviation Press, in Chinese). This book of year 1994 is out of print
[2] Chi L P and Cai X 2004 *Int. J. Mod. Phys.* B **18** 2394
[3] Li W and Cai X 2007 *Physica* A **382** 693
[4] Jung W S, Wang F Z and Stanley H E 2008 *Europhys. Lett.* **81** 48005
[5] Latora V and Marchiori M 2002 *Physica* A **314** 109
[6] Deng W B, Guo L, Li W and Cai X 2009 *Chin. Phys. Lett.* **26** 118901
[7] Xiong F, Liu Y, Si X M and Ding F 2010 *Acta Phys. Sin.* **59** 6889 (in Chinese)
[8] Yan X Y and Wang M S 2010 *Acta Phys. Sin.* **59** 851 (in Chinese)
[9] Wang J W and Rong L L 2009 *Acta Phys. Sin.* **58** 3714 (in Chinese)
[10] Xing C M and Liu F A 2010 *Acta Phys. Sin.* **59** 1608 (in Chinese)
[11] Watts D J and Strogatz S H 1998 *Nature* **393** 440
[12] Barabasi A L and Albert R 1999 *Science* **286** 509
[13] Albert R and Barabasi A L 2002 *Rev. Mod. Phys.* **74** 47
[14] Boccaletti S, Latora V, Moreno Y, Chavez M and Hwang D U 2006 *Phys. Rep.* **424** 175
[15] Newman M E J 2003 *SIAM Rev.* **45** 167
[16] Barrat A, Barthelemy M, Pastor-Satorras R and Vespignani A 2004 *Proc. Natl. Acad. Sci. USA* **101** 3747
[17] Colizza V, Barrat A, Barthelemy M and Vespignani A 2006 *Proc. Natl. Acad. Sci. USA* **103** 2015
[18] Guimera R, Mossa S, Turtschi A and Amaral L A N 2005 *Proc. Natl. Acad. Sci. USA* **102** 7794
[19] Amaral L A N, Scala A, Barthelemy M and Stanley H E 2003 *Proc. Natl. Acad. Sci. USA* **97** 11149
[20] Gautreau A, Barrat A and Barthelemy M 2009 *Proc. Natl. Acad. Sci. USA* **106** 8847
[21] Li W and Cai X 2004 *Phys. Rev.* E **69** 046106
[22] Zhang J, Cao X B, Du W B and Cai K Q 2010 *Physica* A **389** 3922
[23] Liu H K, Zhang X L, Cao L, Wang B H and Zhou T 2009 *Sci. Chin.* Ser. G **39** 935
[24] Bagler G 2008 *Physica* A **387** 2972
[25] da Rocha L E C 2009 *J. Stat. Mech.* P04020