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Research Article

Connection Characteristics and Hierarchical Structure of China's Urban Network-Based on the Communications Technology Service Industry

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Considering the importance of China's digital economy, industrial Internet, and high-quality development, this study analyzed China's urban network from the perspective of the communications technology service industry. Three sub-networks (R & D, sales, and investment) and a comprehensive network were constructed. The density, centrality, and cohesive subgroups of the above network were identified. The results show that: (1) cohesion of urban networks in China is weak and resource sharing is low. (2) From west to east, the urban network forms a multilevel diamond structure in the periphery, a parallelogram structure in the semiperiphery, and a triangle structure in the center. (3) The spatial distribution of cohesive subgroups is scattered, disobeying the first law of geography. By constructing sub-networks and a comprehensive network, the subnetworks that dominate China's urban networks were identified and their typical characteristics described. This study clarifies the technical support pattern behind China's digital economy development and industrial internet construction and provides a basis for policy-makers to optimize the country's high-quality development in the future.

1. Introduction

Since the 1980s, in the context of the third wave of economic globalization, factors of production and product markets worldwide have been integrated, and capital flow around the world has accelerated, shifting the regional and spatial organization of the global economy from the static hierarchical model to the dynamic network model [1]. Cities serve as the primary places and important carriers of economic activities. The flow of factors and enterprise cooperation between cities results in the formation of urban networks. The correlation characteristics and spatial patterns of urban networks can reflect the organizational structure and topographic layout of economic activities, which is important in guiding a rational layout of economic activities. Urban network research has become a hot issue and attracted the attention of many academics.

Among several theoretical constructs, the space of flows [2] and world city network theories [3] still play an important role in urban network research. In particular, the application of the world city network theory, which stems from the space of flow theory, involves a transformation in theoretical research paradigms whereby relationships are analyzed instead of conventional structures. Urban network research has been greatly enriched and supported by this theory. In terms of methodological approaches, researchers are still seeking to improve the models and methods to allow the identification of urban networks. Luthi et al. [4] conducted an empirical analysis of the applicable scale of the chain network model. They found that the top-down method from the perspective of large-scale advanced production and service industry firms is more suitable to identify the world city network, while the bottom-up method that focuses on important enterprise companies in a specific region is a more suitable model to study regional urban networks. Neal et al. [5] proposed a bipartite projection to identify enterprise or city contacts more accurately, given that "strong connection does not necessarily mean great power." Regarding the research content, network hierarchy, and node centrality, studying the factors that influence network formation and the impact of network embedding on other networks remains part of the basic research material of urban networks [6–8]. As urban network research is intensifying, the existing paradigms are no longer limited to measuring network structure characteristics and improving models and methods. More researchers have guided their efforts to determine the causal and developmental mechanisms of urban network formation, as well as the diversity and heterogeneity of networks [9].

At present, urban network research in China focuses on three perspectives: first, to depict the urban network through traffic flows, such as highway [10], railway flow [11], and airflow [12]; second, to determine the relationship between cities through studies on information flow, including information flow carried out on social platforms, such as Sina Weibo [13], QQ group [14], Douban [15], and the network migration information flow reflected in the Baidu migration index [16]; third, to analyze the enterprise network, using multienterprise paradigms, such as the Chinese enterprise firms listed in Fortune Global 500 [17] that list the top 500 companies [18, 19], and single enterprise approaches, such as automobile [20, 21], financial [22], and logistics enterprises [23]. Enterprise organization is the key actor in the urban network [3], making it a priority in urban network research and providing a new theoretical growth point for urban spatial interactions [24]. With the innovations in global information technology and the deepening of informatization, the communications technology service industry has become an important medium of economic and societal ties between cities. This industry includes a chain of raw material suppliers, equipment manufacturers, technical service providers, telecom operators, and end customers. Research and development of fifth-generation (5G) communication, cloud computing, big data, the Internet of Things, blockchain, artificial intelligence, and other fields are key drivers in China's scientific and technological innovation. Concurrently, the industry is an important power source for China's future urban economic development, supplying technological support and facilities for developing the digital economy and the construction of the industrial Internet. The "14th five-year plan" features innovation as a key strategy to accelerate the digital economy, leading to new advantages and high-quality development. The communications technology service network, as a novel perspective of urban network research, clarifies the spatial pattern of China's digital economy and industrial Internet, technology R & D, and facilities layout. Additionally, this industry sector reflects the organizational structure and connection characteristics of China's urban network. The layout of the communications technology service industry and the effective utilization of communications technology play an important role in improving the urban economy and promoting structural optimization.

An influential model of urban network construction is the chain network model. The model uses a complete network to simulate the organizational structure of the enterprise, based on the assumption that connections generally exist between any two branches; thus, it does not make specific judgments on effective and invalid connections within the enterprise [25]. For example, in a communications technology service enterprise, close exchanges between R & D centers are effective contacts; the relative lack of contact between R & D centers and sales outlets is characterized as invalid. The headquarters-branch model is another common model for building urban networks. The model uses a three-level tree structure to simulate an enterprise organization, reflecting the control relationship of headquarters over branches at all levels. However, the model does not consider the cooperative relationships between various sectors within the enterprise [26]. For example, the R & D center must cooperate closely with other technology branches. The zoning core algorithm determines the connection between enterprises according to the key role of central cities in the network, considering the geographical characteristics of enterprise connection, but failing to fully consider whether there is actual business cooperation between enterprises [27]. Zhao et al. [17] put forward the "compromise network model." The model proposes a standardized classification of functions and strict screening of organizational relations, effectively avoiding the redundant connections of the chain network model and the oversimplifications of the headquarters branch model. The study uses the "compromise network model" as a reference and introduces a simplified version based on the characteristic connections of the division of labor and cooperation among the headquarters, R & D institutions, sales institutions, and invested enterprises in the communications technology service industry. The study integrates and optimizes the chain network and headquarters-branch models, constructs subnetworks and comprehensive networks, and offers a more detailed representation of China's current urban network.

This study identified the relationships between the communications technology service headquarters and all branches and between branches, and constructed three subnetworks: R & D city network (R & D network), sales city network (sales network), investment city network (investment network), and an integrated city network (comprehensive network). Adjusting our focus on cities at the level of the prefecture and above (Chinese mainland cities, including Hong Kong), the model describes the overall characteristics of China's urban network, including node centrality, correlation patterns, and cohesive subgroups, and discusses the matching relationships between centrality and power and the development stage of cohesive subgroups. Research outcomes are expected to enrich research on China's urban network and help identify the technical support pattern behind the development of the digital economy and construction of the industrial Internet. Further, outcomes can provide a basis for policy-makers to optimize China's future urbanization and the construction of urban agglomeration areas. This study aims to build a comprehensive network through sub-networks and identify the development stage to explore the mechanisms that drive the construction and evolution of the network. Exploring the entirety, equilibrium, centrality, power, cohesive subgroups, and other characteristics of comprehensive networks using the same data standards helps identify the heterogeneity of networks. The paper is divided into three main sections. Section 2 describes the process of network construction, research methods, and data sources. Section 3 presents the overall and central characteristics, spatial correlation patterns, and cohesive subgroup characteristics of China's urban networks. Section 4 discusses the matching relationship between centrality and power and the stages of development of cohesive subgroups.

2. Network Construction, Research Methods, and Data Sources

2.1. Construction of Urban Network. Defever's classification scheme of multinational corporations distinguishes six branches based on the separation of functions: headquarters, R & D, production, sales, business, and office [28]. In building the model, the emphasis of the communications technology service industry on R & D, the market-driving business strategy, and the supporting role of capital flow in technology R & D activities have been considered. Based on the relationships between headquarters and R & D centers and each R & D center, headquarters and sales organizations, and headquarters and invested enterprises, the R & D, sales, and investment networks were constructed. A comprehensive network was generated by superimposing the three networks. The city network is then projected through the association between different functional institutions in the communications technology service industry. The organizational structure of Huawei, ZTE, and other enterprises suggests close information and technology exchanges between the R & D centers of the same enterprise in different cities. Therefore, this study assumes that multiple R & D centers of the same enterprise are interconnected, in addition to their connection with the headquarters. Thus, the R & D network is constructed based on the chain network model (Figure 1(a)). The key consideration in building the city network is the connection between different cities. Through investigation and interviews, we found that the connection between the sales departments of the same enterprise in different cities is weaker than that in the same city, whereas connections are evident primarily between the headquarters and each sales department. Therefore, the sales network is built based on the headquarters branch model (Figure 1(b)). The construction of the investment network follows the same principle as that of the sales network (Figure 1(c)). In the final step, the above networks are superimposed to form a comprehensive network (Figure 1(d)).

Obtaining data on branch size to construct the city network has been challenging. Hence, the number of branches was estimated from the service values of an enterprise in a city using the method of simplifying the data matrix by Yao et al. [29]. According to the proportional relationship between the annual capital investment in technology R & D, investment behavior, and total annual sales, the weights of the R & D institutions, invested enterprises, and sales institutions were calculated to be 20, 7, and 1, respectively. (The capital investment in technology R & D, investment behavior, and total sales data of 30 enterprises were obtained from the 2019 annual reports of the 30 enterprises. By calculating the average value, the proportion of the three activities for the 30 enterprises was approximately 20 : 7 : 1). In contrast, the flow of capital, technology, personnel, and other elements between different branches are usually bidirectional, and the flow of elements in different directions is difficult to scale [20]. Therefore, the connection matrices of the subnetwork and comprehensive network are a (0, 1) Boolean matrix and a weighted undirected matrix. Based on the above correlation model and combined with the relational projection idea, a 39×39 R & D network, 111×111 sales network, 109×109 investment network, and 175×175 comprehensive networks are built.

2.2. Research Method. An urban network is composed of multiple nodes and their connections. Its construction usually follows the node subgroup network process. Nodes are the supporting elements of the network, and subgroups are important bridges between nodes and the network [18]. In urban network research, attention is directed not only to the integrity and consistency of the networks but also to the connectivity, control, and indispensability of nodes and subgroups [30].

2.2.1. Network Density. Network density is obtained by dividing the number of actual connections in the network by the number of theoretical connections to measure the integrity of an urban network [31]. With higher density, the urban network assumes a higher degree of integration, stronger cohesion, and closer communication between the nodes. The calculation formula is as follows:

$$D = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} d(i, j)}{n(n-1)}, \tag{1}$$

where D is network density; N is the number of nodes; and $d(i, j)$ means the link size between nodes i and j.

2.2.2. Centrality. Regarding centrality measures, social network analysis does not consider the strength of the links between nodes and only measures "bridging" ability, including the indirect links between the three nodes. Neal's transformation centrality and control model considers the number of element flows between nodes and global indirect links [32]. The former focuses on analyzing the centrality and influence of nodes and individual networks from a local perspective, while the latter emphasizes the control and dominance of nodes over the entire network, reflecting the power of nodes in the network [33]. This study discusses the matching relationship between urban centrality and power by calculating and analyzing the centrality of the global urban network and individual nodes.

(1) Centrality Measures in Social Network Analysis. The concept of centrality applies to both nodes and networks. Node centrality is indicated by degree centrality, which

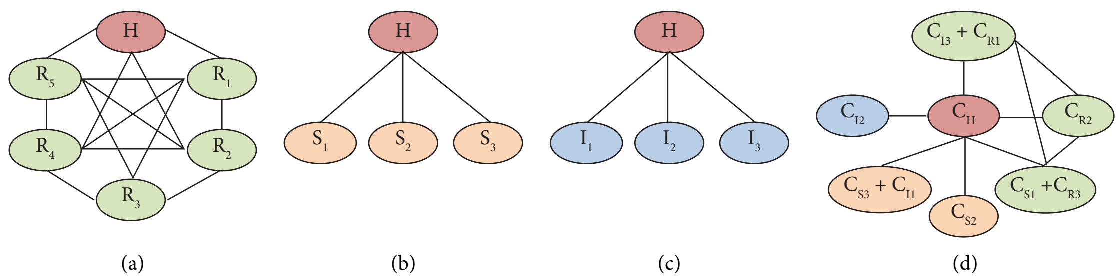

Figure 1: Network association model. networks: C, comprehensive; H, headquarters; I, investment; R: R & D; S, sales. (a) R & D network. (b) Sales network. (c) Investment network. (d) Comprehensive network.

measures how central the location of a node is in the network. The centrality of the network is described by centralization, which estimates the degree of difference between individual nodes in the network. Three measures of centrality are commonly used: degree centrality, betweenness centrality, and closeness centrality, which reflect indispensability, control, and the spatial accessibility of nodes or networks, respectively [31].

Centrality measures are calculated as follows:

$$C_{\mathrm{AD}}(i)=\sum_{i\neq j}X_{ij},$$
$$C_{\mathrm{AB}}(i)=\sum_{j=1;k=1;j\neq k\neq i}^{N}\frac{N_{jk}(i)}{N_{jk}}, \quad (2)$$
$$C_c(i)=\frac{n-1}{\sum_{j=1;j\neq i}^{n}d_{ij}},$$

where $C_{\mathrm{AD}}(i)$ is the degree centrality of node i, X_{ij} the correlation degree between nodes i and j; $C_{\mathrm{AB}}(i)$ is the betweenness centrality; $N_{jk}(i)$ the number of shortest paths between nodes j and k through node i and N_{jk} represents the number of shortest paths between nodes j and k; $C_C(i)$ is the closeness centrality; and d_{ij} the shortest path distance between nodes i and j.

Centralization is calculated as follows:

$$C_{\mathrm{AD}}=\frac{\sum_{i=1}^{n}\left(C_{\mathrm{AD_{max}}}-C_{\mathrm{AD}}(i)\right)}{(n-1)(n-2)},$$
$$C_{\mathrm{AB}}=2\times\frac{\sum_{i=1}^{n}\left(C_{\mathrm{AB_{MAX}}}-C_{\mathrm{AB}}(i)\right)}{(n-1)^2(n-2)}, \quad (3)$$
$$C_c=\frac{\sum_{i=1}^{n}\left(C'_{\mathrm{AP_{MAX}}}-C'_{\mathrm{AP}}(i)\right)}{(n-2)(n-1)}\times(2n-3),$$

where C_{AD} is the degree of centralization$C_{\mathrm{AD_{MAX}}}$ the maximum value of degree centrality; C_{AB} is the betweenness centrality and $C_{\mathrm{AB_{MAX}}}$ the maximum value of betweenness centrality; C_C is the closeness centralization; $C'_{\mathrm{AP_{MAX}}}$ the maximum value of closeness centrality; and C'_{AP_i} the closeness centrality of node i.

(2) Centrality Measures of Transformation Centrality and Control. Neal proposed the transformation of the centrality and control models to measure the status and capture the ability of the city network structure to promote resource agglomeration or diffusion [32]. The method comprises "the scale of the connection network that can be effectively mobilized" and indirect links to account for centrality [20] and to determine the relationship structure of the network more accurately. The transformation control is calculated as follows:

$$\mathrm{AP}_i=\sum_{j}^{n}\frac{r_{ij}}{C_j}, \quad (4)$$

where AP_i is the transformation control of city i, C_j the degree centrality of city j, and r_{ij} the strength of the link between city i and j.

2.2.3. Cohesive Subgroup. In social network analysis, the secondary groups formed by closely related actors in the network are called cohesive subgroups [31]. In this study, we performed a cohesive subgroup analysis to examine the relationship between the nodes in the network and to decipher the importance of connectivity between subgroups. To this end, the convergence of iterated correlations (CONCOR) was used to divide China's urban network into cohesive subgroups. In this procedure, the correlation coefficients of each row or column in the network matrix are calculated repeatedly. After multiple iterative calculations, the number of cohesive subgroups and the city nodes in each subgroup are expressed in the tree view. Finally, the relationship between subgroup density was obtained to analyze the relationships and contacts between the subgroups [31].

2.3. Data Sources. The top 100 communications technology service enterprises in China in 2019, published by the Communication Industry Network (https://www.ccidcom.com), have been selected, and the data on their headquarters, R & D centers, and sales organizations has been collected. Data on the location of investment companies and corporate relationships required for this study were compiled from the National Enterprise Credit Information Publicity System, Tianyancha, and other corporate credit investigation systems. The data on urban economic and social development are obtained from the Statistical Yearbook of China and the Statistical Yearbook of China's Cities in 2020. Based on the collected data, the number of cities and their links vary across networks. The R & D, sales, investment, and comprehensive networks comprise 39 cities with 1130 links, 111 cities with 3840 links, 109 cities with 1368 links, and 175 cities with 30,450 links, respectively. Administrative boundaries have been obtained from 1 : 400 map data published by the basic geographic information center of the State Bureau of Surveying and Mapping (https://ngcc.sbsm.gov.cn/). The drawing number is GS (2016) 2556, and the base drawing was not modified.

3. Characteristics of China's Urban Network

3.1. Overall Characteristics. The comparison of network densities (Table 1) shows that the R & D network has the largest density score (0.2362), and the actual correlation between cities accounts for 23.62% of the theoretical correlation. The ratio for the remaining networks does not exceed 10%, showing that R & D network cities are closely linked and share resources. The cohesion among other network cities is weak, and the degree of resource sharing is low. As the core sites in the competitiveness of the communications technology service industry, R & D centers have strict location requirements and are primarily distributed in large cities with concentrated scientific research institutions (40.14% of the R & D centers of the top 100 enterprises are located in Beijing, Shenzhen, and Shanghai), which impacts the network scale. Network density is limited by the network scale to some extent, and small-scale networks often have a high density [31]. The R & D network scale (39) is significantly smaller than that of the sales (111), investment (109), and comprehensive networks (175); thus, its density and degree of connection between cities are high.

Differences in network centralization indicate that the R & D network is the most balanced of the examined networks. Accessibility between the investment network nodes was slightly poor. The sales and comprehensive networks' "intermediary" center polarization is evident. The data in Table 1, show that the centralization degree of the R & D (0.4723) and the investment networks (0.4441) is low, indicating small differences in the centrality degree of each node; therefore, network polarization due to many links between nodes appears rare. The scores for the betweenness centrality of the sales (0.5345) and comprehensive networks (0.5465) are relatively high, indicating that these rely on individual nodes for transmission, resulting in network imbalance. Across all networks, the closeness centrality score of the investment network was the highest (0.4827), indicating that the accessibility between the investment network nodes was slightly poor.

3.2. Feature of Cities' Centrality. Based on the relationships between the different functional branches of the communications technology service industry, a contact matrix for the R & D, sales, investment, and comprehensive networks was built. Ucinet software was used to measure the degree of centrality, betweenness centrality, and closeness centrality of the network nodes. The natural fracture method in ArcGIS10.2 was used to divide the centrality degree of each node into five categories to estimate the central position and spatial differentiation characteristics of the urban nodes in the network [34].

Figure 2(a) shows the overall spatial pattern of the constructed R & D network and its core cities. Shenzhen, Shanghai, Beijing, and Chengdu recorded the top four centrality scores (Table 2), indicating strong connections, a strong "intermediary" function, and a high possibility of spatial interaction with other cities. The four cities represent the scientific and technological innovation core of the eastern Guangdong-Hong Kong-Macao Greater Bay Area, the Yangtze River Delta Urban Agglomeration, Beijing-Tianjin Hebei Urban Agglomeration, and western Chengdu-Chongqing urban agglomeration, respectively; the cities are also fast becoming core nodes of the R & D network of China's communications technology service industry. Hangzhou, Xi'an, Nanjing, Wuhan, Hong Kong, Guangzhou, and Dongguan also ranked highly. Of these, Wuhan and Xi'an, as core cities of the urban agglomerations in the middle reaches of the Yangtze River and the Guanzhong Plain, respectively, are major nodes of the R & D network in the central and western regions based on their high degree and betweenness centrality scores. Overall, the R & D network core cities capture the actual layout of eastern, middle, and western China.

The sales network is characterized by clusters of cities with high centrality scores along the Beijing-Shenzhen axis and the east; the network is further supported by provincial capital cities, forming a multicore distribution pattern (Figure 2(b)). Of the cities with the top 10 scores (Figure 2(a), Table 2), Shenzhen, Hangzhou, and Beijing belong to the first level (degree centrality scores of 47–69), while Jinan, Nanjing, Wuhan, Guangzhou, Shanghai, Suzhou, and Wuxi belong to the second level (degree centrality scores of 14–46). The distribution of these cities along the Beijing-Shenzhen line and in the east reflects the spatial layout of the economic sector: the eastern region features high economic development and consumption levels, and the sales network overlaps with this layout. Most provincial capital cities comprise the third-level core cities (with degree centrality scores of 8–13). As important nodes of the sales network, these cities are distributed across all provinces, forming a multicore spatial pattern that is further supported by the provincial administrative centers.

The investment network features cities with high-centrality scores in the east and low-centrality scores in the west. Hefei and Shenyang are typical cities in this network with a high centrality score. The core cities of the investment network are primarily distributed in the eastern and central regions, and the centrality of the western cities is low (Figure 2(c)). These characteristics are consistent with the pattern of the spatial organization of China's economy [35], indicating that the investment behavior of the communications technology service industry reflects the characteristic behavior of the "economic man." Hefei occupies a more prominent central position in the investment network compared to that in the R & D and sales networks (Table 2), which reflects the city's active role in scientific research,

Table 1: Overview of network characteristics.

Index	R & D network	Sales network	Investment network	Comprehensive network
Network density	0.2362	0.0711	0.0455	0.0474
Mean degree centrality	8.974	7.82	4.917	7.669
Mean betweenness centrality	13.641	65.865	82.679	114.869
Mean closeness centrality	19.603	46.486	40.486	43.93
Degree of centralization	0.4723	0.5664	0.4441	0.56
Betweenness centrality	0.1489	0.5345	0.349	0.5465
Closeness centrality	/	0.3908	0.4827	0.3597

Note. / indicates that the closeness centrality of the R & D network approaches 0 and is not displayed.

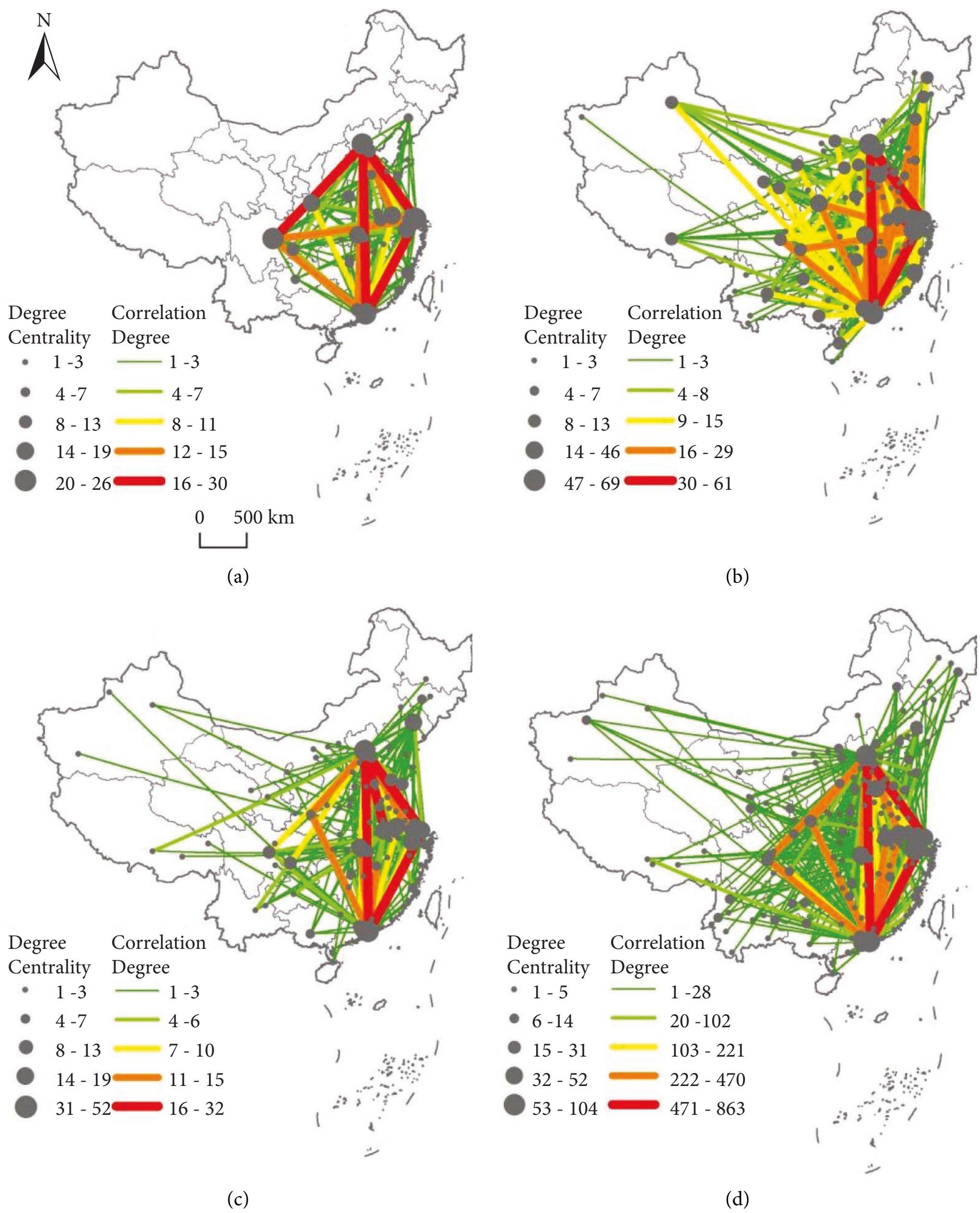

Figure 2: Hierarchical divisions and spatial distribution of degree centrality and relevance of the cities for each network. (a) R & D network. (b) Sales network. (c) Investment network. (d) Comprehensive network.

education, and modern manufacturing industry as a sub-central city of the Yangtze River Delta urban agglomeration. Shenyang shows a strong “bridging” capacity, as it is directly related to many cities in terms of investment activities and as an overall important, high-centrality city in northeast China. These data highlight the transformation of Shenyang from a

Table 2: Centrality measures for each network in the top 10 cities.

Rank	R & D network						Sales network					
	City	Degree centrality	City	Betweenness centrality	City	Closeness centrality	City	Degree centrality	City	Betweenness centrality	City	Closeness centrality
1	Shenzhen	26	Shenzhen	115.62	Shenzhen	23.602	Shenzhen	69	Shenzhen	2387.329	Shenzhen	72.848
2	Shanghai	26	Shanghai	111.851	Shanghai	23.457	Hangzhou	64	Hangzhou	1956.144	Hangzhou	70.513
3	Beijing	25	Beijing	72.703	Beijing	23.457	Beijing	57	Beijing	1033.813	Beijing	67.485
4	Chengdu	22	Chengdu	41.355	Chengdu	23.03	Jinan	46	Jinan	947.147	Jinan	63.218
5	Hangzhou	19	Dongguan	37.081	Hangzhou	22.619	Nanjing	38	Shanghai	415.255	Nanjing	60.44
6	Xi'an	18	Xi'an	31.168	Nanjing	22.353	Wuhan	36	Wuhan	252.494	Wuhan	59.783
7	Nanjing	17	Hangzhou	28.659	Xi'an	22.353	Guangzhou	36	Nanjing	97.596	Guangzhou	59.783
8	Wuhan	16	Hong Kong	23.192	Wuhan	22.093	Shanghai	33	Guangzhou	71.977	Shanghai	58.824
9	Hong Kong	13	Nanjing	23.179	Hong Kong	21.714	Suzhou	33	Wuxi	48.964	Suzhou	58.824
10	Guangzhou	12	Wuhan	16.154	Guangzhou	21.591	Wuxi	33	Suzhou	35.32	Wuxi	58.824
Rank	*Investment network*						*Comprehensive network*					
1	Shenzhen	52	Shenzhen	2080.654	Shenzhen	64.286	Shenzhen	104	Shenzhen	5497.934	Shenzhen	71.02
2	Beijing	49	Beijing	1747.953	Beijing	63.529	Beijing	92	Beijing	3731.205	Beijing	67.969
3	Shenyang	30	Hefei	1009.418	Shanghai	55.959	Hangzhou	74	Hangzhou	2736.438	Hangzhou	63.273
4	Hefei	29	Shenyang	720.376	Shenyang	55.102	Shanghai	52	Jinan	1351.758	Shanghai	58.784
5	Shanghai	24	Wuhan	439.505	Hefei	55.102	Nanjing	52	Shanghai	1202.622	Nanjing	58.586
6	Suzhou	19	Shanghai	410.369	Suzhou	51.923	Wuhan	49	Hefei	1065.531	Wuhan	58
7	Wuhan	19	Nanjing	405.179	Wuhan	51.675	Jinan	48	Wuhan	789.385	Suzhou	57.616
8	Hangzhou	18	Suzhou	382.275	Nanjing	51.675	Suzhou	48	Suzhou	677.083	Jinan	57.237
9	Nanjing	17	Hangzhou	273.256	Hangzhou	50.467	Zhongshan	38	Nanjing	624.68	Zhongshan	55.414
10	Huangshi	12	Huangshi	266.736	Guangzhou	48.869	Wuxi	36	Shenyagn	495.266	Wuxi	55.414

heavy industry to a high-end equipment manufacturing center [36].

The centrality scores of the cities that comprise a comprehensive network reflect a distinct hierarchy. Bound by the Hu Line, the southeast region is a dense area of high-level cities, whereas the northwest shows the opposite trend (Figure 2(d), Table 3). Shenzhen, Beijing, and Hangzhou are classified as first-level core cities; Hangzhou plays an important role in the communications technology service industry. Shanghai, Nanjing, Suzhou, Wuxi, Hefei, Wuhan, Zhongshan, and Jinan are second-level central cities. They are the leading cities in the communications technology service industry in the Yangtze River Delta urban agglomeration, the urban agglomeration in the middle reaches of the Yangtze River, the Guangdong-Hong Kong-Macao Greater Bay Area, and the Shandong Peninsula Urban Agglomeration, respectively. The third-level core cities include Shenyang, Chengdu, Xi'an, Hong Kong, and Guangzhou. Chengdu and Xi'an are important cities in western China and play an innovative and exemplary role in advancing the communications technology service industry in their respective regions; the investment centrality and sales centrality scores for Shenyang are relatively high, but the R & D centrality is low (Table 2). The lack of innovation platforms is likely the reason behind the low development of its communications technology service industry, a problem encountered in many cities in northeast China [36]. Dongguan, Huangshi, Chongqing, and 38 other cities are fourth-level core cities. The degree centrality value is generally higher than the average value of 7.669, and the closeness centrality and betweenness centrality values are lower than the average values (Table 1); these findings indicate that the fourth-level cities have more direct links to the outside world. However, the communication costs with other cities are high, and "bridging" is discouraged. Jiaxing, Nanchang, Huainan, and 121 other cities belong to the fifth level, with centrality values lower than the average level. These cities comprise the budding nodes of the urban network.

3.3. Connection Patterns of the Urban Network. The natural fracture method in ArcGIS10.2 was used to divide the degree of correlation of the city of each network into five categories to identify the backbone structure and correlation patterns of the urban network [34]. The R & D network assumes a diamond structure that largely contains all related nodes (Figure 2(a)). Shenzhen, Shanghai, Beijing, and Chengdu are not only the top 4 cities regarding centrality but also the top 4 connected cities. The sum of their connectivity scores accounts for 49.38% of the total score in the R & D network. As the apexes of the diamond structure, the above cities are interconnected and radiate outward to form the frame of the R & D network.

The sales network in the east forms a characteristic triangle, with a "funnel" effect (Figure 2(b)). The connectivity scores for Shenzhen, Hangzhou, Beijing, Shanghai, and Suzhou bring them into the top 5 cities, accounting for 51.02% of the total connectivity score. The combined connectivity score of 27 provincial capitals accounts for 50.94% of the total score, resulting in many interconnected provincial capital cities in the sales network. The connection direction of the western core provincial capital results in a "funnel" effect upon the main structure formed by the cities in the east. Few low-centrality nodes or small networks are developed in the western provinces or regions, reflecting the uneven correlation across the east and west of the sales network.

The investment network forms a parallelogram structure that shrinks eastward (Figure 2(c)). This configuration is particularly evident compared with the diamond structure of the R & D network. The structure reflects the strong connections between Beijing and Shenzhen, Hefei, Shanghai, Xi'an, and other eastern and northwestern cities; connections with Chengdu, Chongqing, and other southwestern cities are relatively weak. Shenzhen is mainly connected to Beijing, Shanghai, Hangzhou, Xi'an, and other cities in the east and northwest. The apexes of the parallelogram are occupied by Beijing, Shanghai, Shenzhen, and Xi'an.

The strong correlation pattern in the comprehensive network (the correlation degree is greater than 103) results in a mostly vertical topography, and the network structure combines elements from the R & D, investment, and sales orientations (Figure 2(d)). From west to east, strong correlations are mainly noted along a south-north axis, such as Beijing-Chengdu-Shenzhen, Beijing-Xi'an-Shenzhen, Beijing-Wuhan-Shenzhen, Beijing-Suzhou-Shenzhen, Beijing-Hangzhou-Shenzhen, and Beijing-Shanghai-Shenzhen. The correlation intensity along the east-west direction is comparatively weak; this finding is related to the lack of cities with high-centrality scores in the west, reflecting the east–west imbalance in the spatial organization of the comprehensive network. In summary, the combined effect of R & D, investment, and sales networks, with Shanghai, Hangzhou, Suzhou, Shenzhen, Chengdu, Xi'an, and Beijing as apex cities, results in multi-level network structures (peripheral diamond, semi-peripheral parallelogram, and central triangle) from west to east.

3.4. Characteristics of the Cohesive Subgroup. China's urban network is divided into eight cohesive subgroups [37] using the convergence of iterated correlations procedure (CONCOR) (Figure 3, Table 4). The constructed map has two distinctive features. First, the subgroups are interrelated and combined through some mechanism, and the spatial distribution is scattered, in contrast to the first law of geography. Subgroup 1 is the largest and includes cities with high-centrality scores, such as Shenzhen, Beijing, and Shanghai, as well as medium- and low-centrality cities, such as Lijiang, Baoshan, and Hechi. These cities are distributed in the eastern, central, and western regions of China. The number of high-centrality cities in the other subgroups is lower than that in subgroup 1; however, the urban spatial distribution characteristics are similar to those of subgroup 1, consistent with the results of Sheng et al. [18] on the cohesive subgroups of China's urban network. The communications technology service industry is mainly based on

Table 3: Centrality hierarchy of the cities of the comprehensive network.

Level	City examples	Centrality	Number
1st	Shenzhen, Beijing, Hangzhou	104–53	3
2nd	Shanghai, Nanjing, Wuhan, Jinan, Suzhou, Zhongshan, Wuxi, Hefei	52–32	8
3rd	Shenyang, Chengdu, Xi'an, Hong Kong, Guangzhou	31–15	5
4th	Dongguan, Huangshi, Chongqing, Hengyang, Weifang, Tianjin, Qingdao, Nanyang, Deyang, Hanzhong, Huizhou, Lijaing, Zhuhai, Jinzhong, Fuzhou	14–6	38
5th	Jiaxing, Nanchang, Huainan, Foshan, Wenzhou, Shijiazhuang, Changchun, Xiamen, Changzhou, Ningde, Wuhu, Baoding, Jinzhou, Langfang, Shanwei	5–1	121

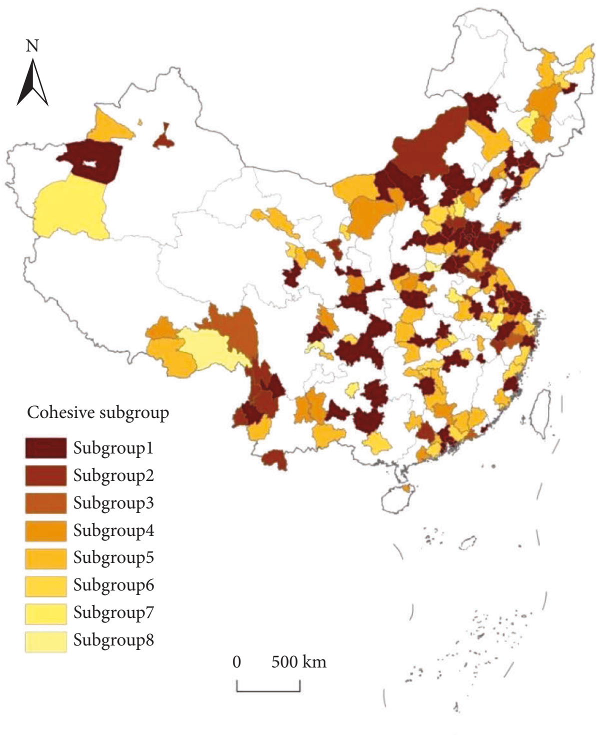

Figure 3: Cohesive subgroups of China's urban network.

Table 4: Analysis results of cohesive subgroups.

Subgroups	City examples	Scale
1	Shenzhen, Beijing, Dongguan, Zhuhai, Hefei, Shanghai, Wuhan, Heze, Ezhou, Jingzhou, Hengyang, Suzhou, Fuzhou, Yangzhou, Taizhou, Suqian, Wuxi, Xi'an, Nanjing, Zhengzhou, Nantong, Hangzhou	68
2	Quzhou, Zhongwei, Dali, Huainan, Zhoushan, Cangzhou, Xuzhou, Zhaoqing, Jinghong, Lianyungang	14
3	Jinhua, Changdu, Shanwei	3
4	Hohhot, Baoji, Huzhou, Yantai, Jinzhou, Urumqi, Luohe, Erdos, Kunming, Haikou	22
5	Linyi, Yinchuan, Heyuan, Handan, Xianning, Jiaxing, Yichang, Changde, Pingdingshan, Yancheng	38
6	Jiangmen, Wenzhou, Ningde, Changzhou, Jiamusi, Huizhou, Guang'an, Ningbo, Bengbu, Yinchuan	19
7	Huangshi, Tongling, Tianjin, Fuyang, Changchun, Hotan, Guiyang, Xuancheng	8
8	Meishan, Xinxiang, Linzhi	3

the Internet and is hardly subject to distance constraints and spatial friction; thus, characteristics of geographical agglomeration are not prominent. Second, the tendency is for cities in the various subgroups to cluster with high-centrality cities: the high-centrality cities clustered in subgroup 1 attract other cities, producing the large-scale subgroup 1. This trend and attraction pattern only occur at the quantitative level, and the low-centrality cities that form subgroups with high-centrality cities show a heterogeneous spatial distribution and resource richness.

4. Discussion

4.1. Relationship between Centrality and Power Matching and the Characteristics of Cities with Different Matching Types. Based on published research [20], degree of centrality, and transformation control force have been selected as statistical measures to explore the relationship between centrality and power in the urban networks. The correction coefficients R^2 between the degree of centrality of each network and the transformation control force are as follows: 0.771, 0.660, 0.847, and 0.818 for the R & D, sales, investment, and comprehensive networks, respectively. These high values indicate an overall positive relationship between centrality and power. The transformation control power of the city is divided into five levels using the natural fracture method [34]. According to the hierarchical matching relationship between degree centrality and transformation control force, five types of cities are identified (Table 5): a city with the highest network centrality and power (HT-CP city) (indicated as levels 11 and 12; i.e., the city's transformation control force and degree centrality are both allocated to the first level or one parameter to the first and the other to the second level); a city with relatively high centrality and power (HR-CP city; levels 22 and 23); a city with medium centrality and power (M-CP city; levels 33 and 34); a city with low centrality and power (L-CP city; levels 44, 45, and 55); and a city with high power and low centrality or high centrality and low power (H-L city; levels 13, 14, 15, 24, 25, and 35).

Cities show the following characteristics: Shenzhen and Beijing are classified as HT-CP cities in any network. As a gathering place for China's universities and scientific research institutes, the center of China's economic development, and

Table 5: City types according to the relationship between centrality and power matching.

Type	Comprehensive network	R & D network	Sales network	Investment network
HT-CP city	Beijing, Shenzhen, Shanghai (3)	Beijing, Shenzhen, Shanghai, Chengdu (4)	Beijing, Shenzhen, Hangzhou (3)	Beijing, Shenzhen, Hefei (3)
HR-CP city	Hangzhou, Nanjing, Chengdu, Wuhan, Xi'an, Guangzhou (6)	Hangzhou, Nanjing, Wuhan, Xi'an (4)	Shanghai, Jinan, Wuhan, Suzhou, Nanjing, Guangzhou (6)	Shanghai, Wuhan, Suzhou, Hangzhou, Nanjing, Shenyang (6)
M-CP city	Hong Kong, Suzhou, Jinan, Chongqing, Fuzhou, Dongguan, Zhongshan (7)	Hong Kong, Guangzhou, Suzhou, Dongguan, Fuzhou, Hefei, Chongqing, Huizhou, Tianjin, Zhengzhou (10)	Hong Kong, Changsha, Hefei, Shenyang, Chengdu, Chongqing, Tianjin (7)	Huangshi, Nantong, Dongguan, Wuxi, Weifang, Guangzhou, Chengdu, Qingdao, Chongqing (9)
L-CP city	Huizhou, Tianjin, Zhuhai, Zhengzhou, Huangshi (159)	Nantong, Zhuhai, Jinan, Changsha, Huangshi. (20)	Weifang, Xianning, Ezhou, Yichang, Nantong (76)	Changsha, Zhongshan, Zhuhai, Jinan, Fuzhou (89)
H-L city	Shenyang (1) (HC-LP city)	Zhongshan (1) (HP-LC city)	Wuxi, Fuzhou, Xi'an, Guiyang, Zhengzhou (19) (HC-LP cities)	None

Note. Figures in brackets represent the number of cities.

the country's largest transportation hub, Beijing is in an absolutely advantageous position regarding technology R & D, market expansion, and attracting investment; thus, the conditions for establishing an R & D center, sales organizations, and production sites for communications technology can be easily satisfied in Beijing. The strategic location and convenient transportation network of Beijing contribute to the development of many links with other cities, reflecting its high centrality. The strong control over the accumulation and allocation of resources to other cities fully reflects Beijing's "capital" effect. Unsurprisingly, well-known communications technology service enterprises, such as Huawei and ZTE, were initially established in Beijing, where they continue to grow. Shenzhen hosts the headquarters of many communications technology service enterprises (the headquarters of the top 100 firms are concentrated in 33 cities, with 17 firms having their head offices in Shenzhen). The Guangdong-Hong Kong-Macao Greater Bay Area, with Shenzhen as one of the central cities, is a densely populated and economically developed area. The "headquarters economy" effect, combined with sufficient labor supply and strong consumerism trends, makes Shenzhen one of the leading cities in China's communications technology service industry; thus, it shows high network centrality and strong dominance and control over other cities. Importantly, Shenzhen and Beijing have supported the balanced development of the communications technology service industry between north and south China.

Each subnetwork comprises typical HT-CP cities. Shanghai and Chengdu are typical examples of HT-CP cities in the R & D network. Shanghai has adjusted its industrial structure since the financial crisis of 2008, supports scientific and technological innovation and R & D development and retains close exchanges with foreign high-tech enterprises; for these reasons, Shanghai is the first choice location for establishing many R & D centers a finding supported in the 2019 report on the Construction of the Shanghai scientific and technological innovation center. The "eastward" strategy implemented by authorities in Chengdu as a means to stabilize its status as a national central city aims to promote a shift of the advanced manufacturing and production services eastward. These initiatives have stimulated the strong growth momentum of Chengdu's communications technology service industry, making Chengdu the only HT-CP city in western China.

Hangzhou is a typical HT-CP city in the sales network. At present, Hangzhou has joined the list of China's new first-tier cities that are characterized by high economic development and consumption levels (Hangzhou ranked 9th in GDP and 5th in per capita consumption level in 2019). Thus, the city can fully meet the demand threshold of products and technologies in the communications technology service industry. Additionally, the logistics industry in Hangzhou has developed rapidly [23], offering excellent channels for product transport and assuming firm control over the accumulation and allocation of resources to other cities. Hefei is a typical HT-HP city in the investment network. It is not only the key investment hub of the communications technology service enterprises but also has the infrastructure to control and allocate resources across the investment behavior chain, acting as a leading city in the investment network.

The emergence of H-L cities, such as Shenyang, Zhongshan, and Wuxi (Table 5), shows that the positive relationship between centrality and power is not absolute. Shenyang emerges as an HC-LP city in the comprehensive network and an HR-CP city in the investment network. Although, this result indicates the city's direct links with many cities in the high-end equipment manufacturing sector, most of the linked cities have limited resources, and thus the index does not grasp the real power of adjusting resources in the network. For example, Zhongshan is an HP-LC city in the R & D network, directly linked with only a few cities. However, most of these cities have large amounts of resources, and the scale of indirect links is sufficiently large to exert great power in the network. Furthermore, a large number of H-L cities in the sales network have been detected; they are all HC-LP cities, indicating that, although many high-centrality nodes in the sales network have been identified, most of them have no real power. Wuxi, Fuzhou, Xi'an, Guiyang, Zhengzhou, and other provincial capitals are

Table 6: Index identifying subgroup development stage.

Index	Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 4	Subgroup 5	Subgroup 6	Subgroup 7	Subgroup 8
Number of HT-CP cities	3	0	0	0	0	0	0	0
Number of HR-CP cities	7	0	0	0	0	0	0	0
Number of M-CP cities	7	0	0	0	0	0	0	0
Number of L-CP cities	0	14	3	22	38	19	8	3
Number of HL-CP cities	1	0	0	0	0	0	0	0
Scale of subgroup	70	14	3	22	38	19	8	3
Density of subgroup	0.194	0	0	0	0	0.005	0	0

Table 7: Density of subgroups.

	Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 4	Subgroup 5	Subgroup 6	Subgroup 7	Subgroup 8
Subgroup 1	0.194	0.022	0.024	0.025	0.024	0.056	0.057	0.01
Subgroup 2	0.022	0	0	0	0	0	0.009	0
Subgroup 3	0.024	0	0	0	0	0.017	0	0
Subgroup 4	0.025	0	0	0	0	0.005	0.011	0
Subgroup 5	0.024	0	0	0	0	0	0.01	0
Subgroup 6	0.056	0	0.017	0.005	0	0.005	0.019	0
Subgroup 7	0.057	0.009	0	0.011	0.01	0.019	0	0.042
Subgroup 8	0.01	0	0	0	0	0	0.042	0

H-L cities in the sales network (Table 5). Although these cities feature high centrality, they cannot mobilize network resources.

4.2. Identification of the Development Stages of Cohesive Subgroups. The development stages of the various subgroups were qualitatively and quantitatively identified by considering the numbers of HT-CP, HR-CP, M-CP, L-CP, and H-L cities, subgroup density, and the scale of subgroup membership (Table 6). The process of subgroup development within the comprehensive networks in China is currently divided into three stages. The first stage is termed the decentralized node stage; that is, each subgroup comprises a decentralized node, node centrality is low, and there are no connections between the nodes. Subgroups 2, 3, 4, 5, and 8 are typical subgroups in the first stage. These subgroups are composed of L-CP cities, and the subgroup density is 0, indicating a lack of links with other cities; in other words, subgroup 1 cities are relatively isolated. The second stage is the pre-network stage. Here, despite the overall low node centrality, weak connections between the nodes are detected, with a tendency to form a network. Subgroups 6 and 7 are typical subgroups in the second stage and are composed of L-CP cities. The network density of subgroup 6 is 0.005, indicating that the cities in this subgroup begin to connect and tend to form a network. In contrast, the network density of subgroup 7 is 0. Considering that the connection density between subgroups 1 and 7 is 0.057 and that between subgroups 1 and 6 is 0.056 (Table 7), it is highly probable that subgroup 7 will connect with subgroup 6 through subgroup 1 [37] and form a network. The third stage is the initial network stage, which is characterized by a distinct hierarchy of node levels, relatively close connections between nodes, and the formation of a network structure. Subgroup 1 is at this stage. It comprises cities with distinct hierarchies and various characteristics, including HT-CP, HR-CP, M-CP, and H-L cities. The network density of subgroup 1 is 0.194 (Table 7), indicating that the cities in this subgroup are closely connected. The connection density between subgroup 1 and other subgroups is >0, reflecting the importance of subgroup 1 as the necessary channel through which other subgroups connect. Thus, subgroups can interconnect through subgroup 1 to complete the urban network structure.

5. Conclusions

The communications technology service industry represents the technical support and infrastructure network of the digital economy and is one of the leading industries contributing to China's high-quality development. This study examined the communications technology service industry in the context of China's emerging urban network research, drew lessons from it, and simplified the "compromise network model." Additionally, subnetworks and comprehensive networks based on the same enterprises have been constructed, and the connection characteristics and hierarchical structure of China's urban networks have been analyzed.

The results of the study show that the urban network cohesion in China is weak, and the degree of resource sharing is low. Beijing, Shenzhen, and Shanghai show high centrality and power. The R & D network assumes a symmetrical global distribution pattern, with Wuhan as the central symmetry node, and Beijing, Shenzhen, Shanghai, and Chengdu as apexes. The sales network forms a multicore distribution structure supported by several provincial capital cities. The centrality of the investment network cities is generally high in the east and low in the west. Hefei and Shenyang show high investment centrality, and these cities can serve as a reference constructing China's industrial Internet. Based on the top national node system of China's industrial internet, Shenzhen, Chengdu, Hefei, and

Shenyang emerge as the national secondary vertex systems of China's industrial internet.

China's urban network is constructed along Beijing-Chengdu-Shenzhen, Beijing-Xi'an-Shenzhen, Beijing-Wuhan-Shenzhen, Beijing-Suzhou-Shenzhen, Beijing-Hangzhou-Shenzhen, Beijing-Shanghai-Shenzhen, and other south-north linkages that form multilevel networks of peripheral diamond, semi-peripheral parallelogram, and central triangle structures from west to east. The south-north backbone line and multilevel structure represent the core axes of China's digital economic development and industrial Internet that radiate across central and western regions to coordinate China's high-quality development plan. According to the relationship between centrality and power matching, Chinese cities can be divided into five categories: HT-CP, HR-CP, M-CP, L-CP, and H-L. Shenzhen and Beijing are HT-CP cities in each network; Shanghai and Chengdu are typical HT-CP cities in the R & D network; Hangzhou in the sales network; and Hefei in the investment network; these findings indicate that cities such as Shenzhen, Chengdu, Hefei, Shenyang, and Hangzhou have the potential to form a national secondary apex system of China's industrial Internet.

The cohesive subgroups of China's urban network are characterized by a scattered spatial distribution, in contrast to the first law of geography. The cities in the cohesive subgroups have a tendency to form groups with high-centrality cities. However, this trend is evident only at the quantitative level, and the low-centrality cities that form subgroups with high-centrality cities show a heterogeneous spatial distribution and resource richness. Thus, it is reasonable to expect a coordinated and balanced development among regions in the context of China's digital economic evolution and to avoid transfer processes from high-centrality to low-centrality cities.

This study refines some of the typical characteristics of China's urban networks into specific networks through the construction of subnetworks. For example, the diamond structure of China's urban networks can be largely attributed to the R & D network orientation. The administrative center orientation is apparent primarily in the sales network, and typical core cities, such as Chengdu, Hangzhou, and Hefei, participate in the R & D, sales, and investment subnetworks. China's urban network, examined from the perspective of traffic flow, has weak spatial dependence, a finding with important theoretical ramifications for the overall layout of China's industrial Internet.

Based on the analysis of the characteristics of the communications technology service industry, this study not only offers a new perspective on the construction of China's urban network in the context of China's digital economy, industrial Internet, and high-quality development. To further explore the mechanisms responsible for the formation of the network structure of the urban communications technology service industry and provides more practical suggestions for developing China's digital economy. The optimization of future urbanization patterns and the construction of urban agglomerations and metropolitan areas are the focus of the authors' follow-up research.

Data Availability

The data of the communication equipment technology service industry can be obtained from https://www.ccidcom.com. The socioeconomic data of cities can be collected from the Statistical Yearbook of China's Cities and the Statistical Yearbook of China.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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