이학석사학위논문

Passenger Flows in the Metropolitan Seoul Public Transporation: Maximum Spanning Tree and Community Detection

서울 수도권 대중교통에서 승객 흐름: 최대신장나무와 지역사회 찾기

2013년 2월

서울대학교 대학원

물리천문학부

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지도교수 최 무 영

이 논문을 이학석사 학위논문으로 제출함

2012년 12월

서울대학교 대학원

물리천문학부

고 정 훈

고정훈의 이학석사 학위논문을 인준함

2012년 12월

위 원 장 강 병 남 (인)

부위원장 최 무 영 (인)

위 원 유 재 준 (인)

Passenger Flows in the Metropolitan Seoul Public Transporation: Maximum Spanning Tree and Community Detection

Jeong Hoon Ko

Supervised by

Professor **Moo Young Choi**

A Thesis for the Degree of

Master of Science

December 2012

Department of Physics and Astronomy

Graduate School

Seoul National University

Abstract

In this thesis, passenger flow of Metropolitan Seoul public transportation system is examined through maximum spanning tree and community detection. The public transportation system, consisting bus and subway, provides major transportation modes to the people. The characteristic of movement of people can be analyzed by the passenger flow data of public transportation system. We divide one station by departure station and arrival station and construct maximum spanning tree of the passenger flow. The degree distribution of the departure stations and arrival stations in the maximum spanning tree follows power law with different exponent according to the time zones. We also investigate the community structure of Metropolitan Seoul. The bus and subway stations are coarse grained by square grid and the modularity maximization method using simulated annealing is employed first to find disjoint node(square area) communities. The disjoint link community, using single-linkage agglomerate method and partition density maximization, is also found to reveal overlapped communities. The distribution of number of links and nodes per community in the disjoint link community also follows power law distribution. These communities can be regarded showing real community

character of Metropolitan Seoul in the sense of the lexical meaning of community.

Keywords: passenger flow, transportation, bus, subway, maximum spanning tree, community detection, modularity, simulated annealing, overlapped community, link community, partition density, power law, simulated annealing.

Student Number: 2011-20388

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Chapter 1

Introduction

Social systems are one of strongly interested system of statistical physics. The large city, in which huge numbers of people are interacting, is indubitably complex system. The transportation system, thus, has been studied in many ways from data analysis to modeling[1–5]. Due to the developed technology we are easily collecting information about human movement using public transportation. In Metropolitan Seoul, most of resident people are using public transportation card for bus and subway and their trajectories are stored in the calculating system. Their getting-on and getting-off time and locations are stored accurately. This information represents how Metropolitan Seoul citizens are circulating in a day in the area.

The station (or bunch of stations in the certain area) can be considered as node and the number of passenger between from one node to another can be considered as weight of link connecting two nodes. The direction of movement is the direction of link. In this setting, the passenger flow is mapping to the weighted directed network. The analysis of complex network is heavily studied[6–9] and we can apply those methods directly.

In this thesis, we examine mainly two subject of analysis, maximum spanning tree and community detection. The maximum spanning tree, which has the opposite definition of more familiar concept, minimum spanning tree, is spanning tree having weight sum not lower than the other spanning tree. The maximum spanning tree(MST) of passenger flow shows core structure of passenger flow because it leaves most important links maintaining connected network. Investigating MST, we examine which stations function as hub of city[2]. In the MST construction we divide each station by departure station and arrival station. This is bipartite network because there is no link between departure stations as well as between arrival stations. Examining MSTs of bipartite passenger flow network we are able to recognize not only which station (or area) is hub, but also the role of hub station such as sink or source. The degree distribution of MST is investigated for different time zones and for the different station type, departure and arrival.

The people forms cluster in their social life according to the similarity, affiliation and other background. The spatial constraint also performs a role of origin of community structure. Even in the big city such as Seoul in Republic of Korea, where the transportation system is well constructed, the people have their own travel radius and the agglomerated behavior of them probably makes community structure in Seoul. The hardware structure of public transportation system has crucial role of shape of community and vice versa. In this thesis, we find community structure of Metropolitan Seoul using the passenger flow data. The community detection problem has attracted much interest and there are heavy research on this theme[10]. We use modularity maximization method, which is most popular method in community detection, and link community detection to reveal overlapping structure. The detected community based on passenger flow data is similar to the literal meaning of community, the people living in a particular area. We can examine how the community structure is formed in the Metropolitan Seoul and hopefully reveal the relation between public transportation systems.

There are four chapters in this thesis: In Chapter 2, we investigate the MSTs of passenger flow and find hub structures. In Chapter 3, we conduct community detection by two methods and reveal the community structures of Metropolitan Seoul for differently categorized data. In Chapter 4, we summarize the results of the study.

Chapter 2

Maximum Spanning Trees of Passenger Flow

2.1 Introduction

The passenger flows can be considered as weighted graph or network, where nodes represent stations and weight of edges represent number of passenger between stations. If there is at least one passenger from station to station we consider two stations are connected, if not disconnected.

To investigate the structure of passenger flow network, the maximum spanning tree is employed. In the graph theory, a tree is an undirected graph without cycle in which any two nodes are connected by simple path[11]. A spanning tree is subgraph of original graph that satisfy the properties of tree. For the weighted graph, we can construct minimum(maximum) spanning tree in which the weight sum of spanning tree is not larger(smaller) than other spanning trees. The minimum spanning tree is widely applicable to the real problems such as laying telecommunication cable problem. The weight can be considered as cost of constructing a link, thus the minimum spanning tree has been more interested than maximum spanning tree. But, in the passenger flows, the larger weight edge is more important than smaller one. Thus the, so-called, maximum spanning tree(MST) is constructed.

The MST is undirected binary network. The weight information is reduced to the structure of spanning tree. The most important links will be remained with the constraint that the network should be connected. The direction information is lost in normal MST. To keep the direction information we divide each station into departure station and arrival station. This bipartite network preserve the direction information. By investigating MST, we can see the core structure of passenger flow easily.

2.2 Method

We first separate each node into the departure one and arrival one. The departure node is connected to arrival nodes only and vice versa. For example, the directed link from node v to node w is mapped to link between $v - out$(departure node) and $w - in$(arriving node) on the bipartite network. We construct MST for this modified passenger flow network. There are several algorithms to find the minimum spanning tree. Two algorithms, Prim's algorithm and Kruskal's algorithm, are mainly used. The maximum spanning tree can be found using same algorithm as minimum spanning tree. In this thesis, Prim's algorithm is modified to find maximum spanning tree. The algorithm is as following[12].

1. Choose a node x arbitrarily from original node set V as a start node. $V_{mst} = \{x\}$.

2. Choose a link $\{u, v\}$ which have weight not less than others where u is in V_{new} and v is not.

3. Node v is added to V_{new} and link $\{u, v\}$ is added to E_{mst}.

4. Repeat 2, 3 until $V_{new} = V$.

5. E_{mst} is constructed maximum spanning tree with V.

The degree distributions of the MST of the departure nodes and arrival nodes are obtained separately.

2.3 Results

We consider Metropolitan Seoul public transportation passenger flows. We first draw MST of subway passenger flows only. The real location of subway stations are depicted in Fig. 2.3. We split each subway station S by two parts, departure station S_{dep} and arrival station S_{arr}. By separating same station according to its direction of flow, the passenger flow network is changed to bipartite network composed by departure nodes and arrival nodes. Fig. 2.2 shows MST of subway station. The solid dots and empty circles represent departure nodes(stations) and arrival nodes, respectively. If the degree is equal

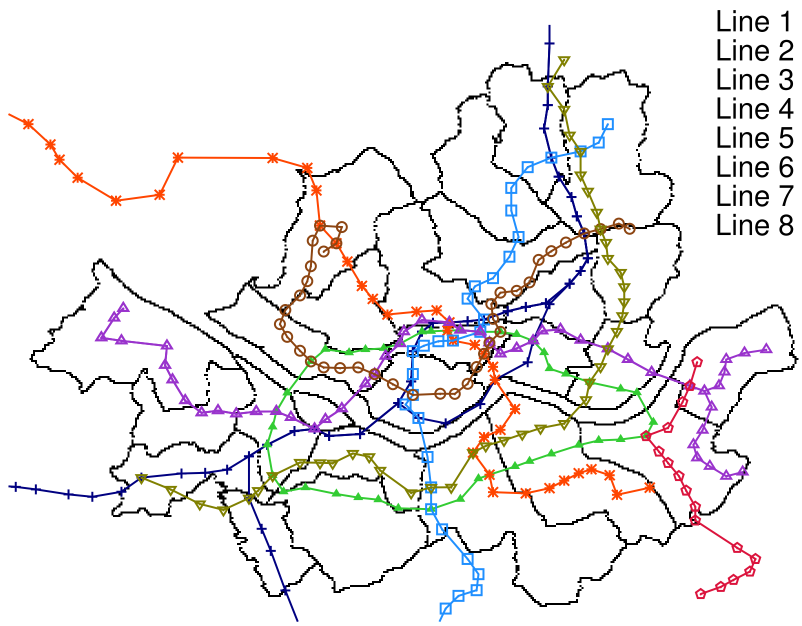


Figure 2.1: Hard structure of Metropolitan Seoul subway system.

or higher than 20, the station names are marked with '-in'(arriving) and '-out'(departing) mark. The number in the parenthesis is degree.

Figure 2.2(a) is for weekday(5 days) all-day passengers. As you can see in Fig. 2.2(a), two stations, Suwon and Cheonho, are hubs of MST, Suwon-in(arriving to Suwon), Suwon-out(departing from Suwon), Cheonho-in(arriving to Suwon) and Cheonho-out(departing from Suwon). Because all-day data contains people going to work and leaving the office, the key stations for commuting people are performing role of hubs. Fig. 2.2(b) and Fig. 2.2(c) are MST for different time zone of weekday. Gangnam, Gwanghwamun, GasanDigitalComplex station is around representative civil center of Seoul. There is a huge number of companies are located. Thus, in the Fig. 2.2(b), these stations are hubs as arriving('-in') stations in the morning as expected. Seoul station (connected to Seoul railway station) has largest degree, thirty-one. It means many people are arriving in Seoul from other region of Korea in the morning. On the other hand, Ganseokogeori and Suwon acts as hubs as departure station. Those two stations are hub for going work people from metropolitan area to Seoul. In the Fig. 2.2(c), the situation is reversed. Most of working people are getting out the office and going back to home. People are going out from center of city, GasanDigitalComplex and Jonggak(close to Gwanghwamun), and arriving near residential area, Suwon and Cheonho. Around KonkukUniv station is a mecca for entertainment of young people. Young people may be gathering there in the evening time.

Now all stations, bus stations and subway stations, are considered together. We coarse-grain stations by square area. This coarse-graining is not only for easy handling, but also for the reasonable approach. The very close stations should be considered as same node actually because we do not get on the transportation for very near distance[3]. In the raw data, bus stations face each other across the street are regarded as different stations, but it is effectively same station in fact. In this reason, coarse-grained approach is reasonable and even convenient.

The weight of link between any square areas including departing and arriving

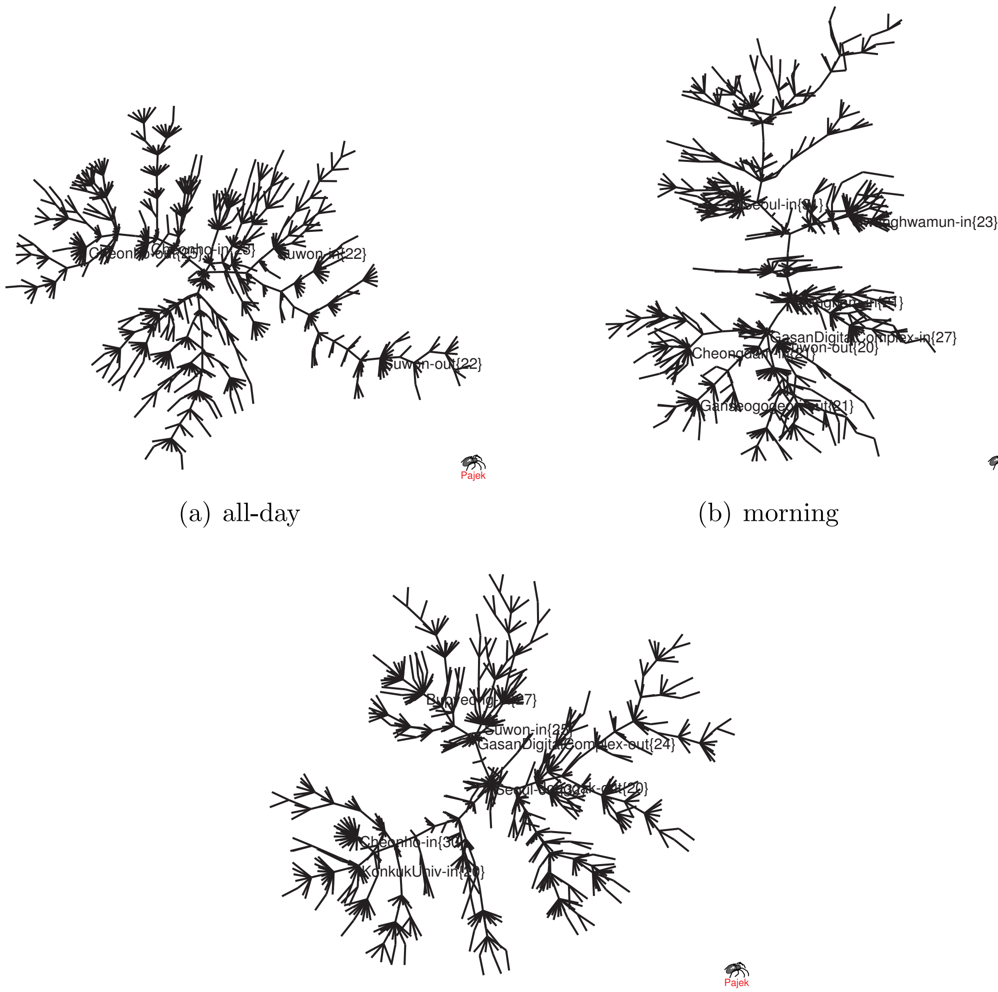
	Bipartite		Undirected
	departure st.	arrival st.	·
Morning	2.33	1.90	2.08
Afternoon	2.07	1.98	1.90
Evening	1.98	2.00	1.89
Night	1.70	2.28	1.80
All-day	2.00	2.00	1.92

Table 2.1: Exponents of power law distribution in different time zones. First two columns contain exponents with bipartite coarse-grained grid. Third one is normal undirected network of grids. The coarse-grained grid size L=433m.

station is increased by one if any passenger's point of departure and the last destination are inside them. We ignore transfer between the departure and the destination, but consider only the first departure and the last destination. We consider bus and subway stations only in Seoul, not whole Metropolitan.

Figure 2.3 shows MST of whole stations. the x and y axis is real location of stations in longitude and latitude coordinate respectively. Figure 2.4(a) to Fig. 2.4(d) show degree distributions of predefined time zone, e.g., morning(7 a.m. to 10 a.m. arrival passenger), afternoon(11 a.m. to 3 p.m. departure and arrival), evening(6 p.m. to 8 p.m. departure) and night(9 p.m. to 11 p.m. departure). All of them show power-law distribution, $p(k) \sim k^{-\gamma}$, and the exponent γ is slightly different according to the time zones. The exponents of degree distribution of different day and time zone are summarized in Table 2.1.

Notice that the exponents of morning and nights are reversed roughly. The concentration of people is stronger in the down town, work area, than the residential area. In the morning time, huge amount of people are arriving in the downtown of city and the hub characteristic of arrival nodes is stronger than departure nodes. Thus the exponent of arrival station is smaller than departure stations(See Fig. 2.4(a) also). When the people are going home from work place, the situation is reversed. Interesting point is that the reversed situation inferred from the exponent behavior occurs at night time, not evening time.



(a) all-day

(b) morning

(c) evening

Figure 2.2: Maximum spanning trees of passenger flows in the Metropolitan Seoul Subway System. Names of some hubs stations are provided with degrees and direction. Pajek program is implemented.

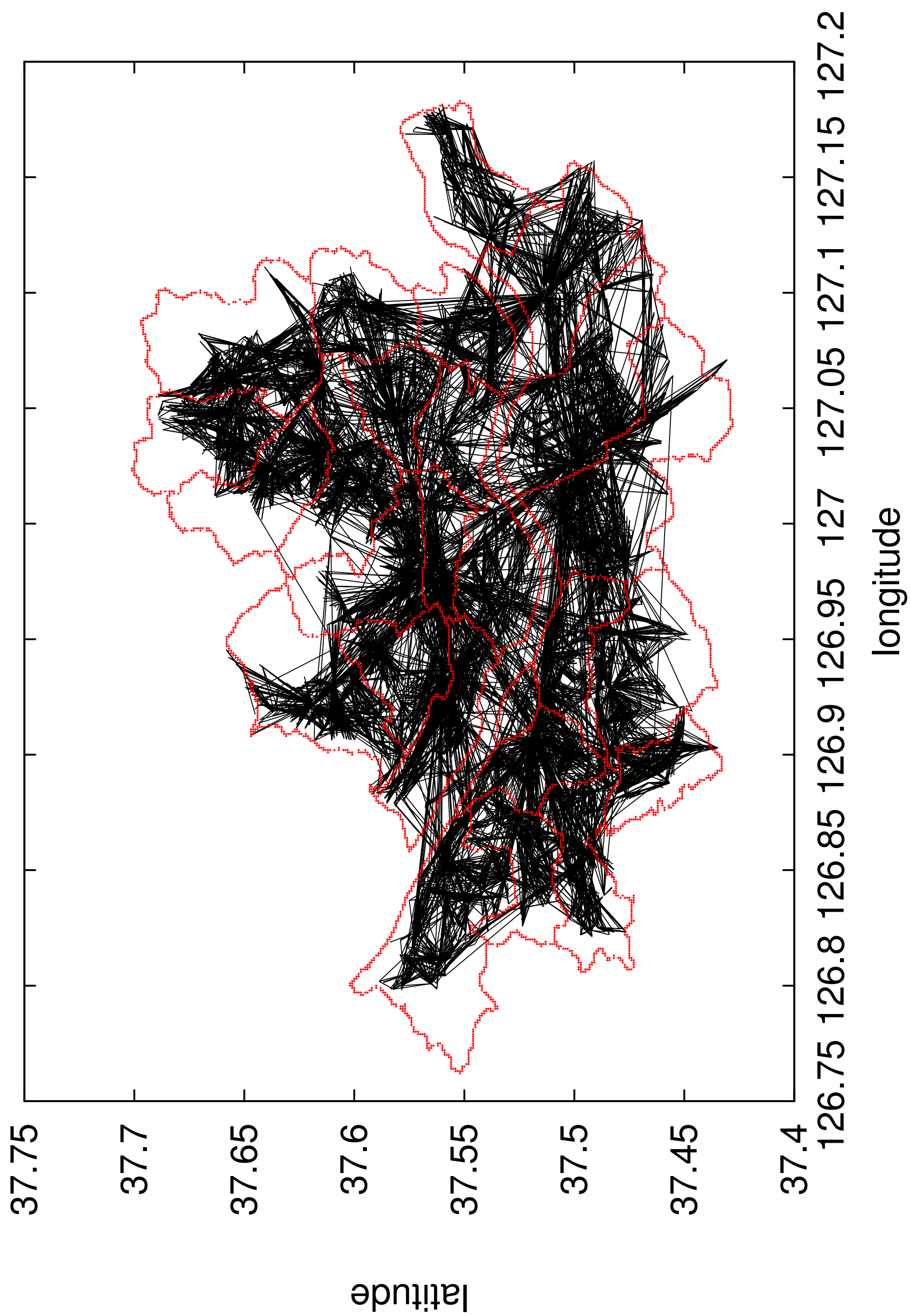
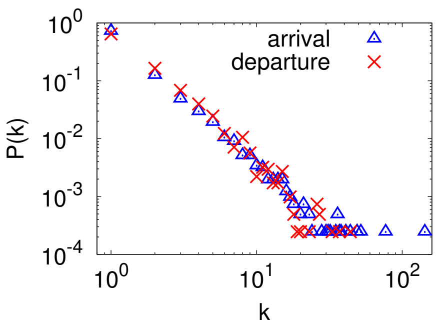
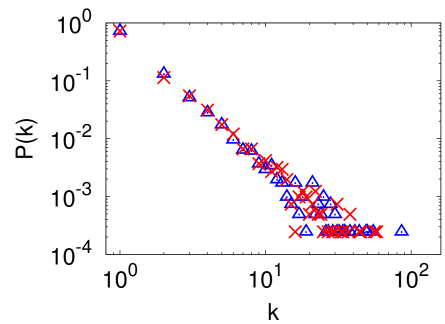


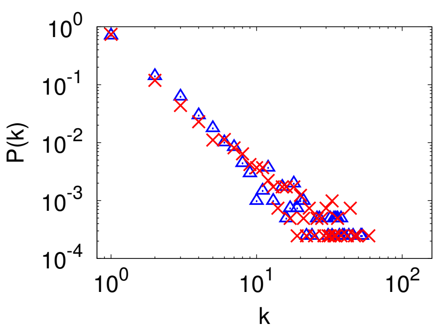
Figure 2.3: Maximum spanning tree of bus and subway station in Seoul.



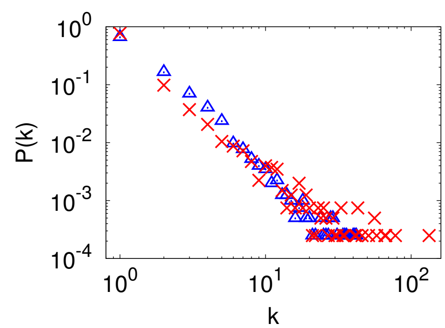
(a) morning



(b) afternoon



(c) evening



(d) night

Figure 2.4: Distribution of degree k of the maximum spanning tree of bus and subway passenger flow in different time zones, plotted on the log-log scale. The cross marks represent departure nodes and the triangle marks represents arrival nodes.

Chapter 3

Community Detection

3.1 Introduction

Most of real world network shows community structures. Community is also called module, cluster and so on [10]. The community structure means the links are connected densely insides the node group and few of links are connected between different groups. The existence of this group comes from the sharing properties of nodes or spatial constraint. In the passenger flow network, the community is close to its literal meaning, the people who live in a particular area or place and communicate and interact frequently. If Seoul Metropolitan really has communities inside of it, the passenger flows can show the community structure because the passenger flow is directly related to the living area.

Revealing communities in the network is called community detection. The difficulty of community detection is that the definition of community is not definite. Thus, there is some arbitrariness to detect communities, and there are many ways to find communities based on slightly different concept of modules. The traditional method is graph partitioning[10], which separate nodes in g groups of equal size and the number of links across the groups is minimal. This method is most intuitive way to find communities, but weakness is predefined group number and group size. We cannot know how many communities are there. One of the modern method to detect community is maximizing modularity, quality function Q. This method has some demerit [17], but it still good way to detect community. The detailed method is written in the next section. The modularity maximization method is node partitioning method, in which nodes are belong to disjoint communities. However, the real network shows overlapped community structure. For example, each individual has many roles in society, such as student, friend, son or daughter, business person and so on. For each role, the individual belongs to different communities. The communities in the city are considered in the same manner. Nodes are stations and each station can belong to different communities. Especially, the hubs stations perform many roles in the city. Therefore we need to detect overlapped structures. In recent days, the methods to identify overlapped communities are invented [16, 19, 20]. One of method is to find disjoint link communities rather than node [16]. This method reveal overlapped communities as well as hierarchical structures in the network. In this thesis, this method is employed also to detect overlapped structures of communities in Seoul Metropolitan.

3.2 Method

3.2.1 Modularity maximization by simulated annealing

The modularity optimization method was first introduced by Newman and Girvan[13]. They define a quality function Q as follows

$$Q = \frac{1}{2m} \sum_{ij} (A_{ij} - P_{ij}) \, \delta(C_i, C_j). \tag{3.1}$$

Newman-Girvan modularity is defined for the undirected binary network. The main idea is comparison between actual density of edges and expected density in the null model for given partition. A null model is somewhat arbitrary in fact. In equation (3.1), A_{ij} is element of adjacency matrix of given network and P_{ij} is the probability that link would exist in null model. $\delta(C_i, C_j)$ is one if node i and node j are belonging to same community and zero if not. m is total number of links in the given network and it is normalization factor. The Newman-Girvan modularity supposes that random network does not have community structure and the probability that there is link between nodes is proportional to degrees of each node. Therefore, P_{ij} is $\frac{k_i k_j}{2m}$ with appropriate normalization factor $2m$. Finally, the Newman-Girvan modularity is

$$Q = \frac{1}{2m} \sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right) \delta(C_i, C_j). \tag{3.2}$$

Equation (3.2) can be generalized to directed weighted network straightforwardly. The degree is replaced by strength(sum of weight of links from a node) and summation is going through each directed links. So, k_i and k_j are replaced by s_i^{out}, s_j^{in} and A_{ij} is replaced by W_{ij} and $2m$ is replaced by total weight sum W considering direction. s_i^{out} means out-strength of node i. Thus, most general expression of modularity is[14].

$$Q_{gen} = \frac{1}{W} \sum_{ij} \left(W_{ij} - \frac{s_i^{out} s_j^{in}}{W} \right) \delta(C_i, C_j). \tag{3.3}$$

Some weakness of this generalized modularity is argued [18], but it is not critical in our problem. The remaining problem is the optimization of this quality function. There is a bunch of method in optimization problem. Simulated annealing is one of popular way based on the statistical physics[15].

3.2.2 Overlapped community detection: Disjoint link community

The modularity maximization method reveals disjoint node communities. To identify overlapped communities, disjoint link community detection is introduced. Each link is assigned to the community and node can be belonging to several communities naturally. In this thesis, we built hierarchical link communities using single-linkage hierarchical clustering. The procedure is as following[16].

1. Start from single link communities(all single links are own communities)

2. Compute similarity S of all nearest link pairs of each node.

3. Merge two communities which have the two closest elements(two closest elements means node pair which have largest similarity and belong to

different communities).

4. Repeat 3 until all links are assigned in one community.

Each step of single-linkage agglomerate procedure, partition density is computed. The partition density of each community is defined as

$$D_c = \frac{m_c - (n_c - 1)}{n_c(n_c - 1)/2 - (n_c - 1)}. \tag{3.4}$$

Then the partition density of whole communities is weighted averaged with the fraction of present links.

$$D = \frac{2}{M} \sum_c m_c \frac{m_c - (n_c - 1)}{(n_c - 2)(n_c - 1)} \tag{3.5}$$

We select optimized link community where D is maximized.

3.3 Results

3.3.1 Modularity maximization by simulated annealing

At first, the communities of subway stations are considered. The stations on the same line are strongly tangled in the same communities[See the Fig. 3.3.1]. Many passenger do not transfer on the subway, the weight of links between same line stations is large. This tendency hides other structures of communities. For example, Gangnam station, which has largest strength, is not only important on the 2nd line subway, but it plays role of hubs of other stations.

Thus, we will introduce later the link community detection to reveal overlapped structures.

Now, the combined passenger flow, subway and bus ignoring transfer on the path, is considered. The Seoul area is partitioned to grids. Considering each stations as own node is not needed and even not plausible. People do not use means of transportation for short distance. There is no weight between very near stations. However, the people using those two stations are obviously belonging to same community. Thus, grid is more plausible than raw stations as a node. And the size of grid can be considered as the unit of community.

Figure 3.3.1 to Fig. 3.3.1 show detected communities of Seoul according to the different size of grids. Different communities are depicted as different shape of box. Naturally, the proximity ties communities. However, when the grid size is below $500m$, the second line of subway structure is aroused. This means $500m$ is about the area of attraction of subway station at least for second line.

We also conduct community detection for different time zones. The community structures are almost same during day but evening and night time the community south side and south east side are merged.

3.3.2 Overlapped community detection: Disjoint link community

As you can see in section 3.3.1 the subway stations on the same line is highly clustered. However, a single station can affiliate numerous communities. In other words, the different communities may share nodes actually. For example, Gangnam station is belonging to 2nd line community in Fig. 3.3.1. But a bunch of people from Bundang area(residential district) commute to Gangnam in real. But this feature is hidden by same line community. To reveal overlapped community we find the disjoint link community rather than disjoint node community. The partition density, eq (3.5) is defined for undirected binary network. Thus we should reduce directed weighted network to undirected binary network. At first, we merge directed links and make undirected network. And we give cut-off fraction to delete links. The weight/strength fraction is calculated for two nodes connected to a link and if one of them are smaller than cut-off fraction, we delete them. Remaining links have weight 1 as binary network. If we do not delete links below cut-off, the remaining binary network is too dense. Even more, the very small number of passenger can be considered noise and the link due to this passenger is not relevant. 4

Figure 3.5 shows link communities sharing selected subway stations. Gangnam station is no more belonging only to 2nd line community(but it still belong to 2nd line community). The link community detection is adequate method to reveal overlapped structure of nodes.

Figure 3.6 shows the distribution of the number of links and the number of nodes per community. The corresponding data is coarse-grained bus and subway stations with grid size L=433m. It follows power-law distribution as expected[16].

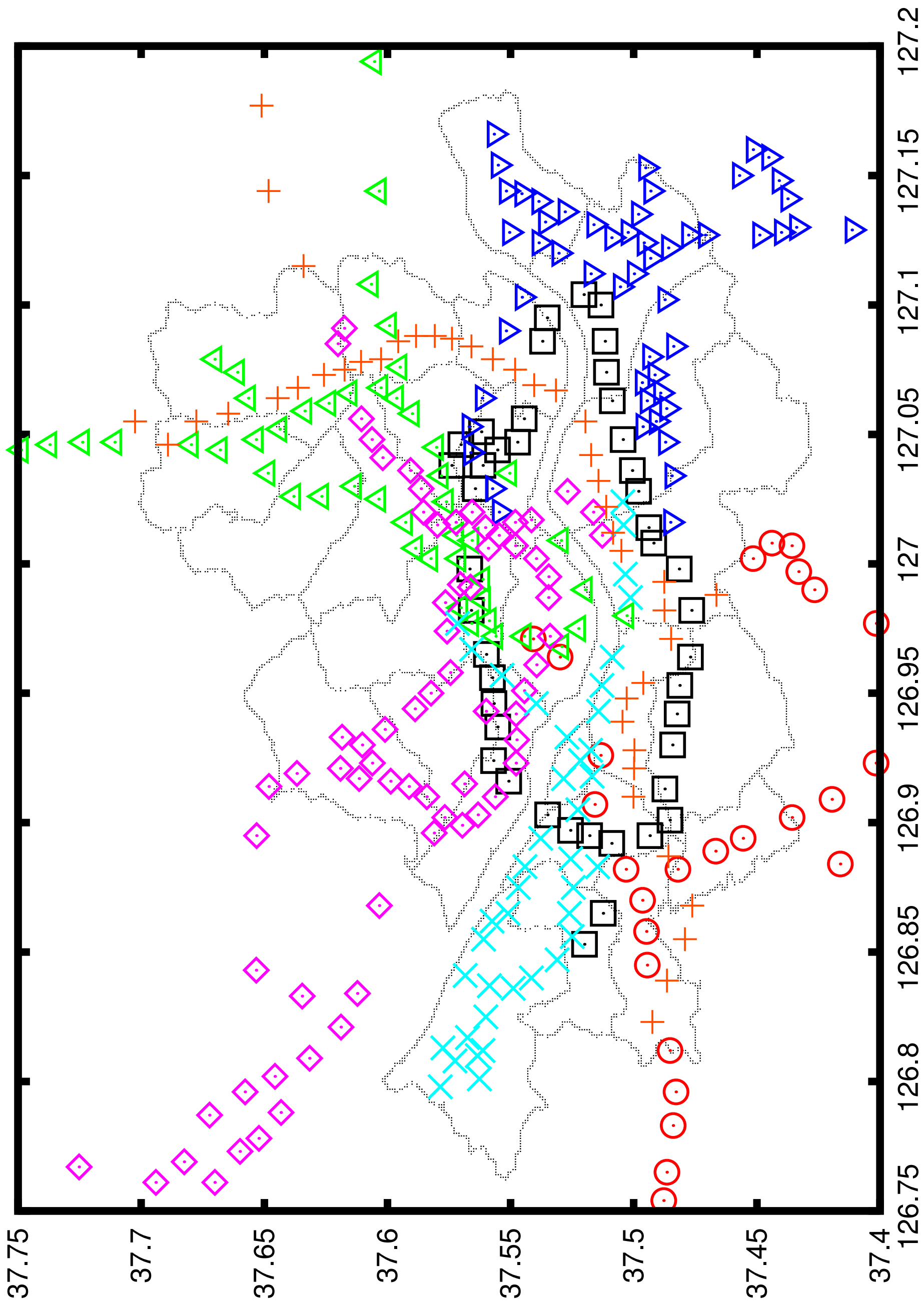


Figure 3.1: Community detection of subway stations using modularity maximization.

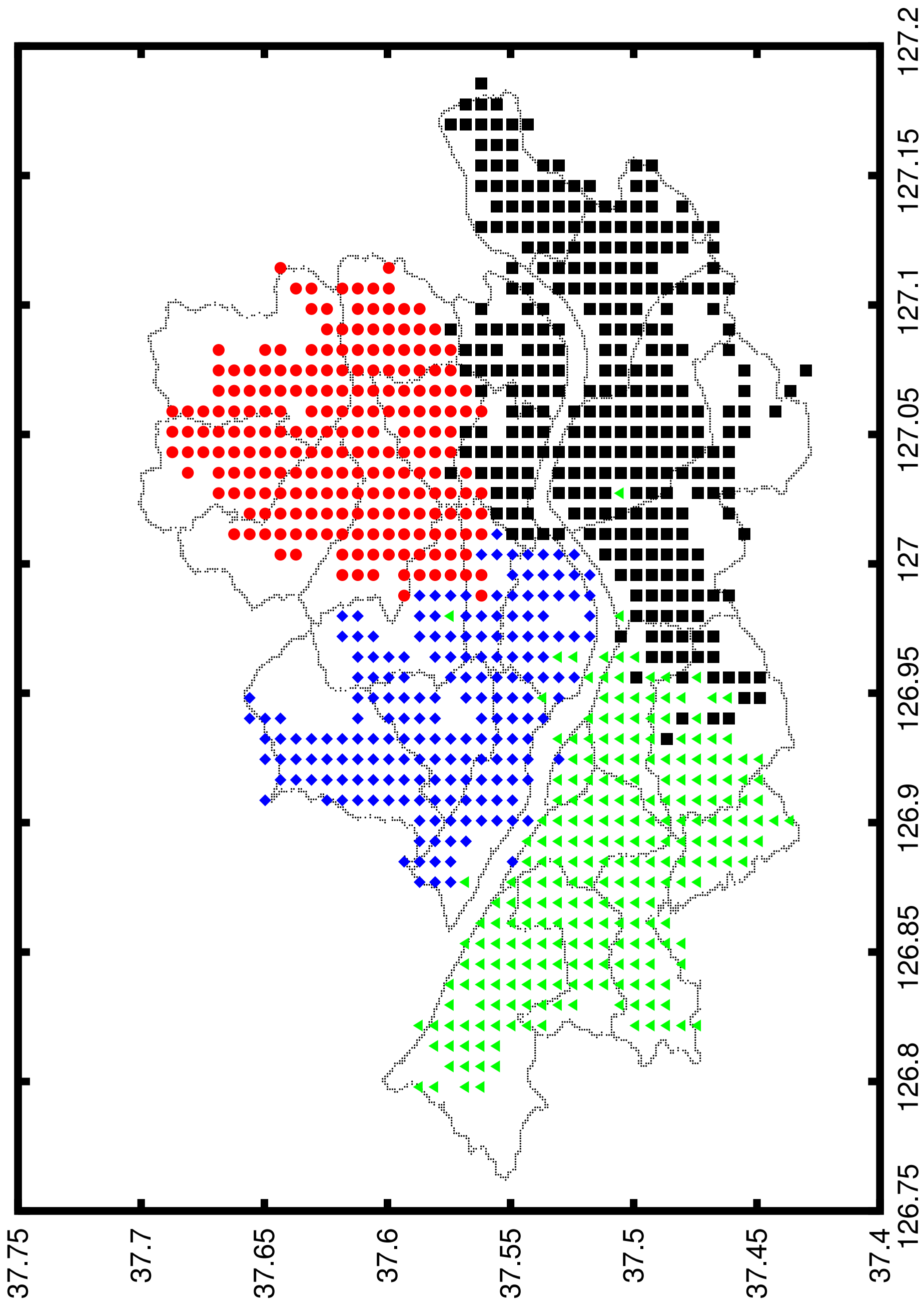


Figure 3.2: Community detection of coarse-grained stations using modularity maximization. L=697m.

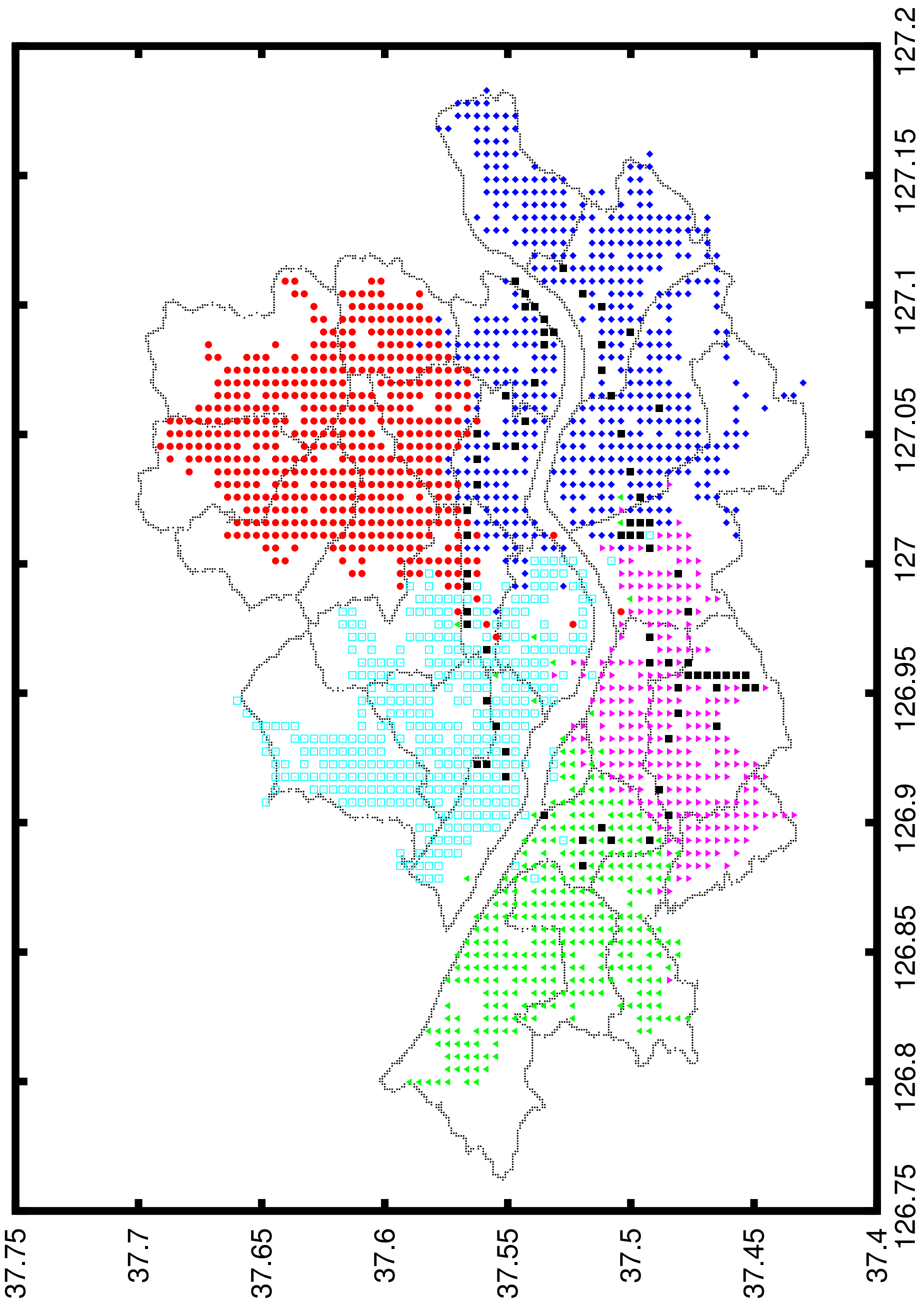


Figure 3.3: Community detection of coarse-grained stations using modularity maximization. L=433m.

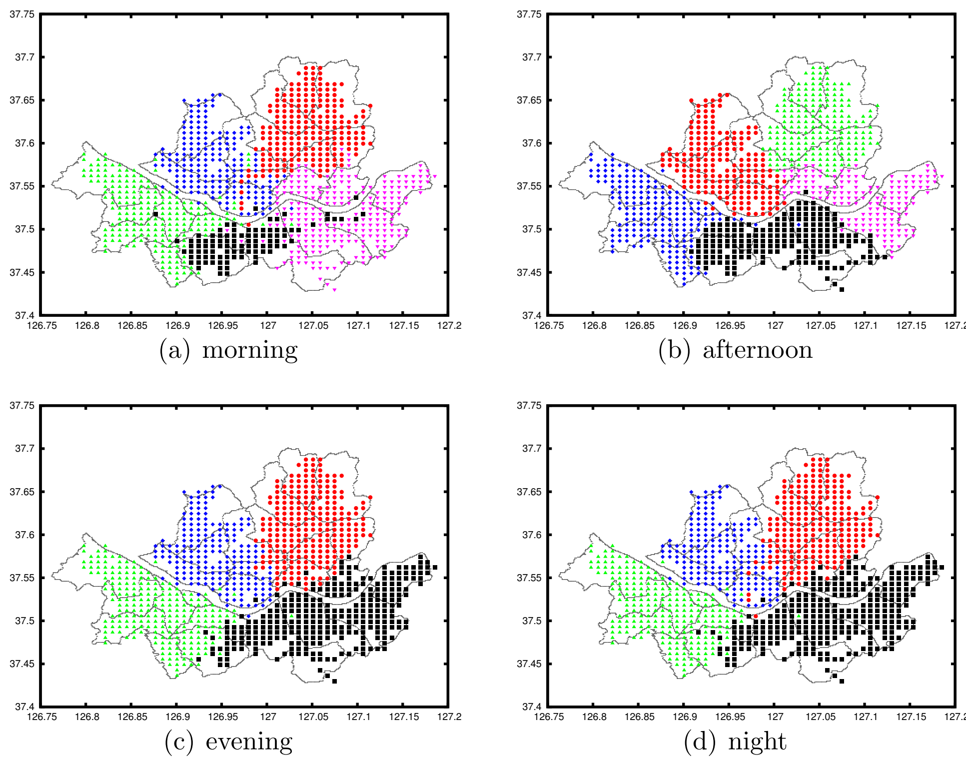
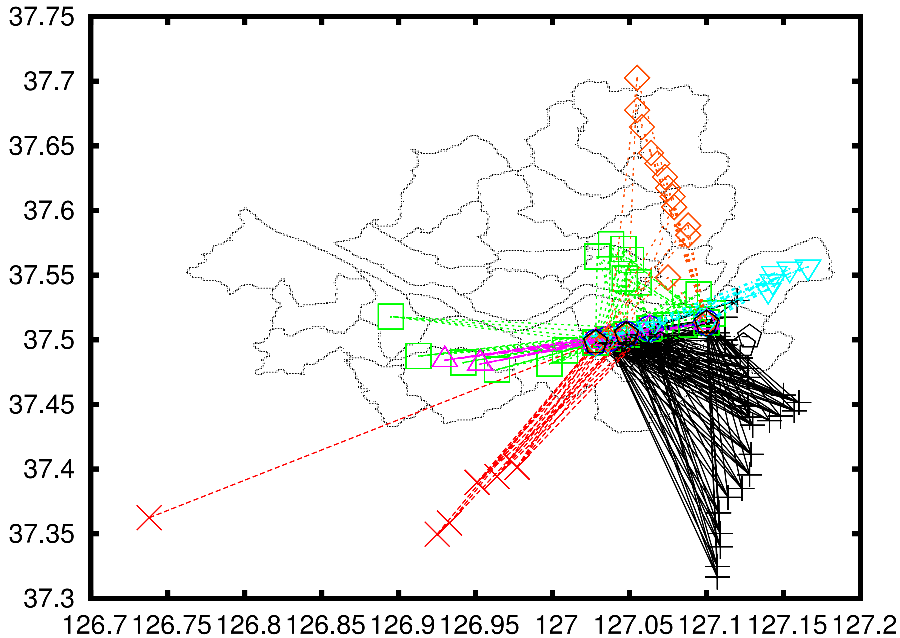
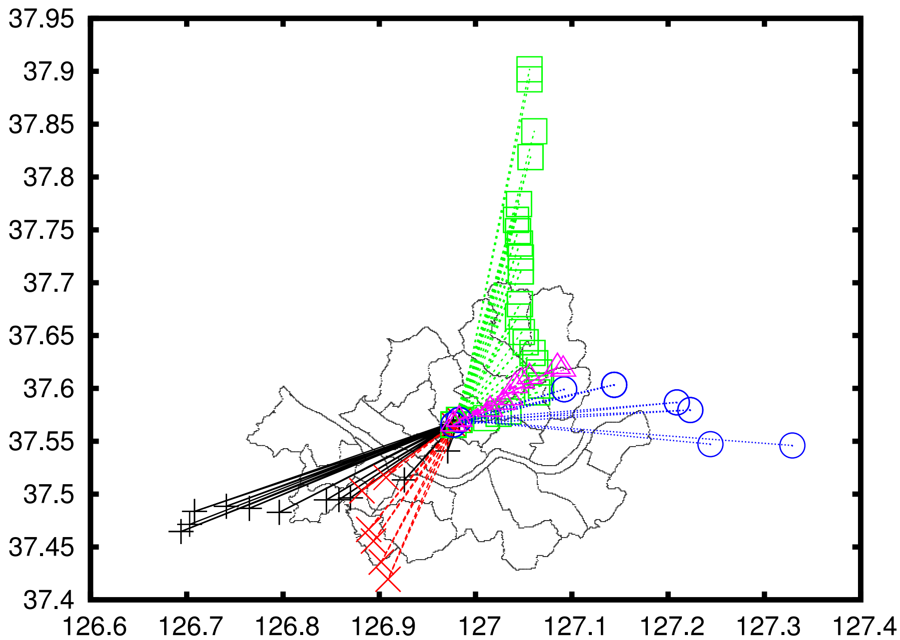


Figure 3.4: Community detection of coarse-grained stations using modularity maximization in different time zones. L=697m

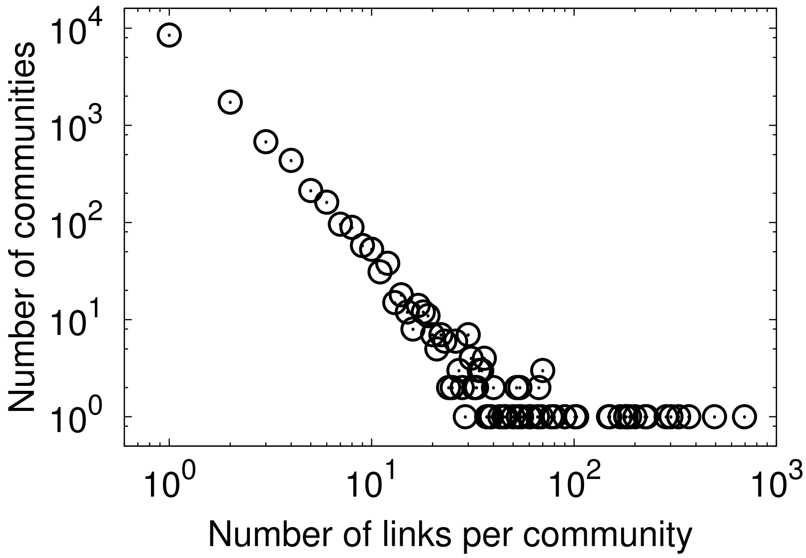


(a) Link community contains Gangnam station

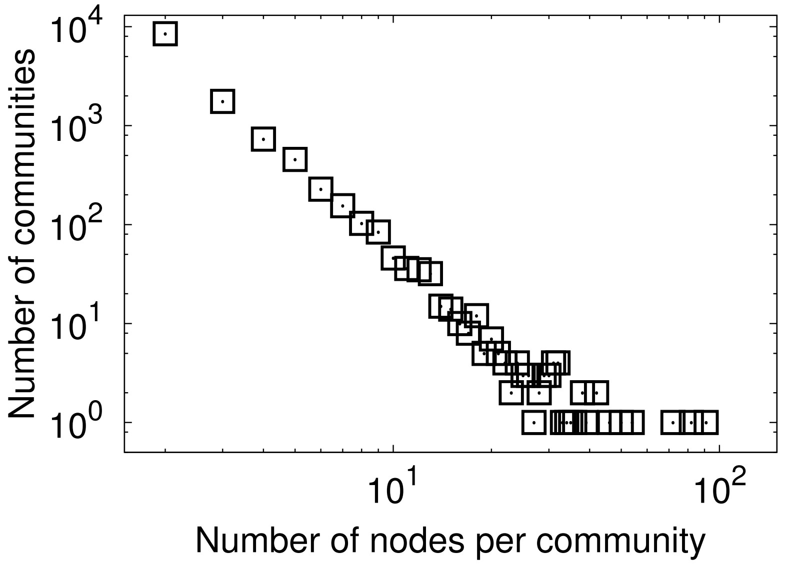


(b) Link community contains Jonggak station

Figure 3.5: Link communities contain selected stations.



(a) Number of links distribution



(b) Number of nodes distribution

Figure 3.6: Number of links per community and number of nodes per community follow power-law distribution. Coarse-grained bus and subway stations are nodes. L=433m.

Chapter 4

Summary

In this thesis, we have investigated the passenger flow data constructing maximum spanning tree and conducting community detection. We have shown that the degree distribution of maximum spanning tree is following power law. The exponents of distribution are different for different time zones. We have found community in Metropolitan Seoul. The disjoint node community, obtained from modularity maximization using simulated annealing, shows there are four to seven communities in Seoul and it depends on the coarse-grained size. The disjoint link community, obtained from single-linkage agglomerate method maximizing partition density, shows overlapped communities for hub stations. The distribution of number of links and nodes per community shows power law distribution.

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국문 초록

본 논문에서는 서울 수도권의 대중교통 시스템에서의 승객 흐름을 최대신장나무와 지역사회 찾기를 통해 살펴보았다. 대중교통 수단인 버스와 지하철은 사람들의 주된 교통 수단으로 제공된다. 사람들의 움직임의 특성은 승객 흐름 데이터를 통해 분석할 수 있다. 이 논문에서는 역을 출발역과 도착역으로 나누어 승객흐름의 최대신장나무를 구성하였다. 최대신장나무에서 출발역과 도착역의 연결 수 분포는 거듭제곱 법칙을 따르며 시간대에 따라 지수는 달랐다. 이 논문에서는 또한 서울 수도권의 지역사회 구조를 연구하였다. 버스와 지하철 역을 사각 격자로 대충 갈기 한 뒤 모듈럴리티 최대화를 도입하여 사각 영역으로 표현되는 노드들로 구분된 지역사회를 구하였다. 단일 연결 합치기 방법과 분할 밀도 최대화를 통해 구분된 링크들의 지역사회를 구하여 중첩된 지역사회를 발견하였다. 한 지역사회 안의 노드 수와 링크 수의 분포는 역시 거듭제곱 법칙을 따른다. 이 지역사회들은 사람들의 실제 이동 자료를 통해 찾았다는 측면에서 실제 서울 수도권의 지역사회 특성을 보여준다고 생각할 수 있다.

주요어: 승객 흐름, 교통, 버스, 지하철, 최대신장나무, 지역사회 찾기, 모듈럴리티, 중첩된 지역사회, 링크 지역사회, 분할 밀도, 거듭제곱 법칙, 시늉 열풀림

학번: 2011-20388

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